The Spectral Dimension of Arctic Outgoing Longwave Radiation and Greenhouse Efficiency Trends from 2003 to 2016

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Manuscript Under Revision

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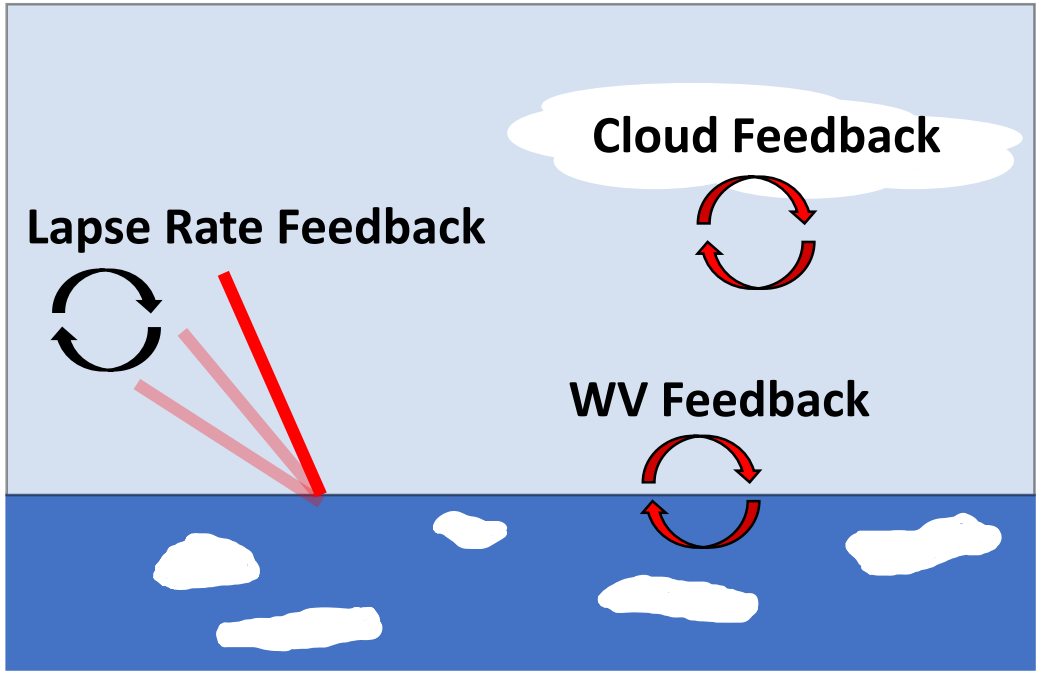
Radiative Implications of a Changing Arctic System

Radiative Responses

- LW feedback processes



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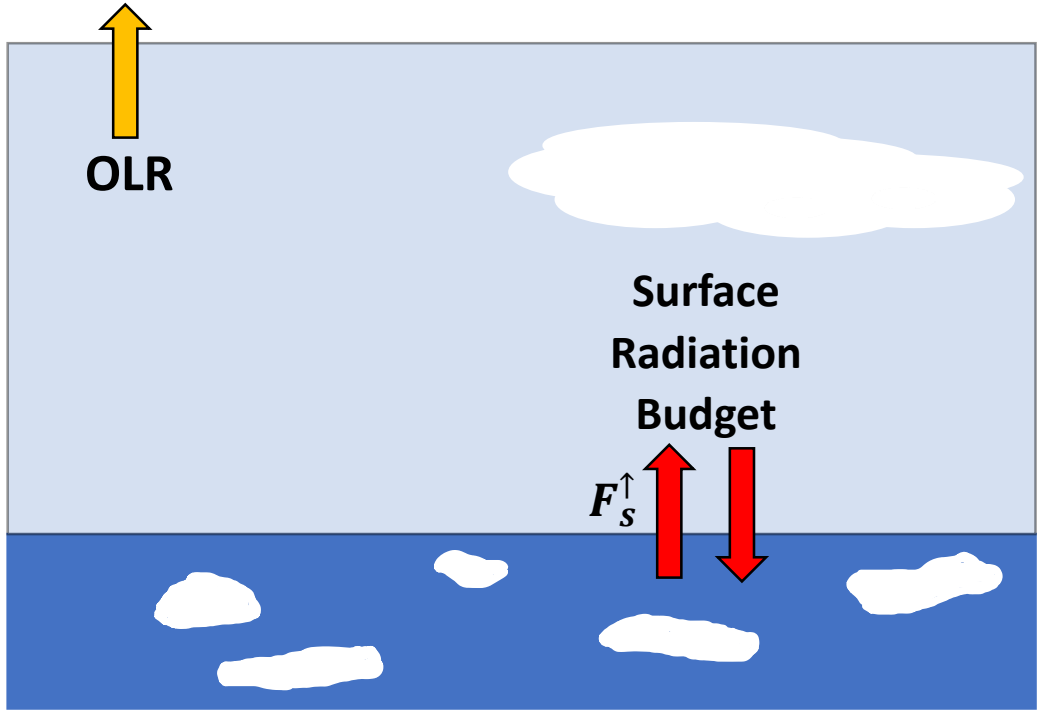

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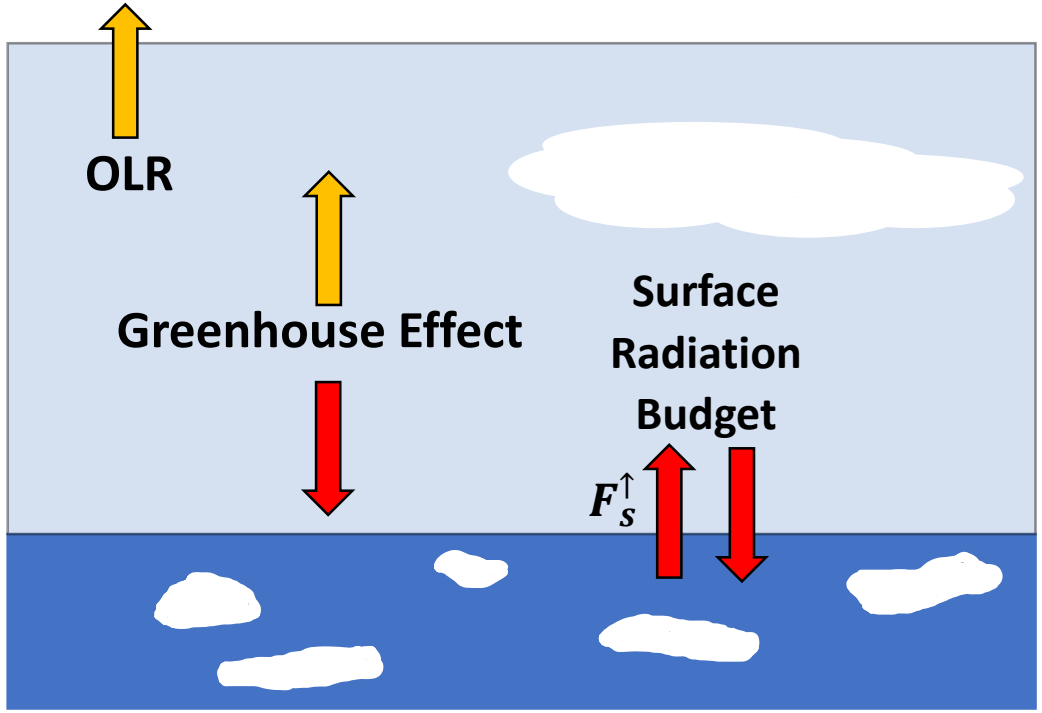

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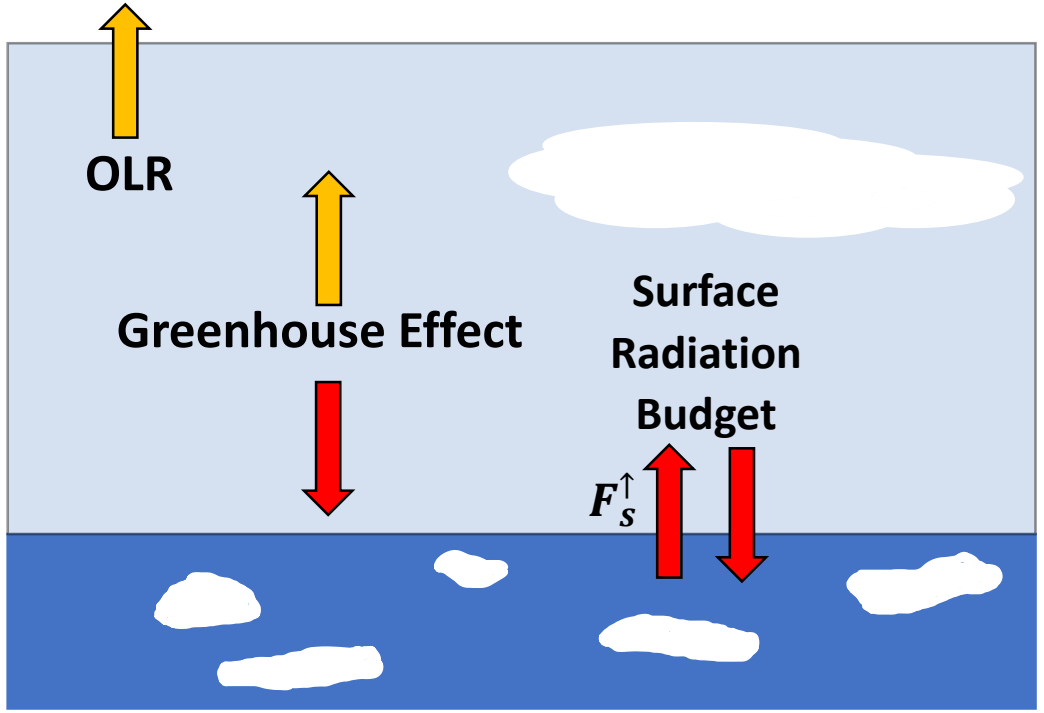
Defining Greenhouse Efficiency

$$\text{GHE}(\nu) = \frac{F_S^{\uparrow}(\nu) - OLR(\nu)}{F_S^{\uparrow}(\nu)}$$

As GHE → 1 , **stronger greenhouse efficiency**



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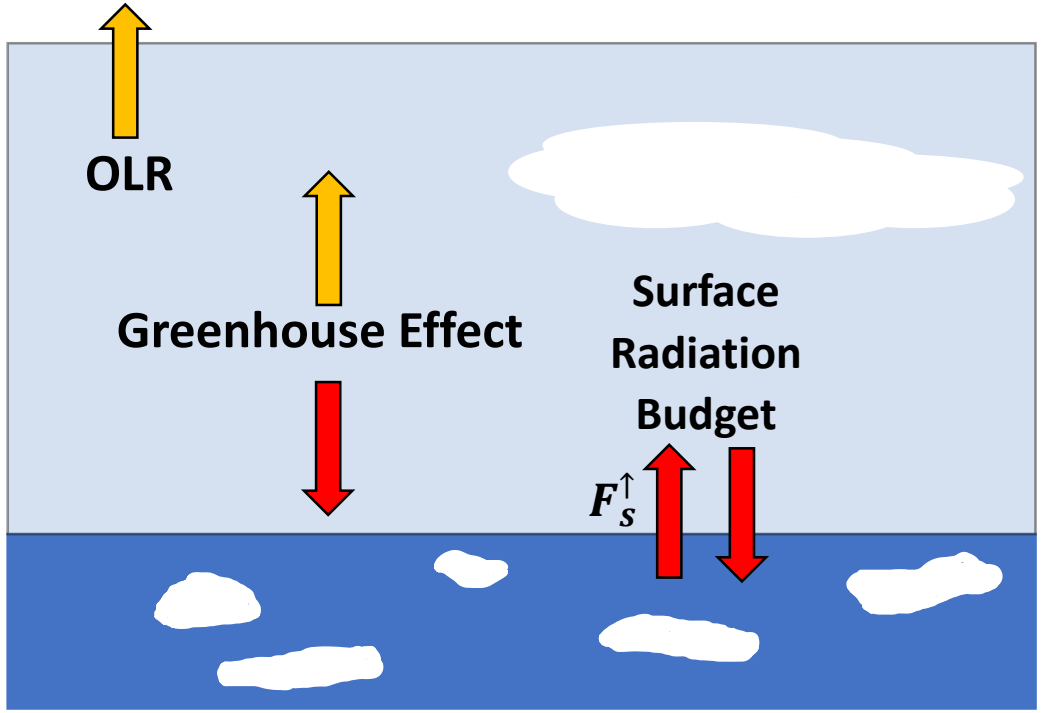

Far-Infrared

- Composes > 60% of Arctic OLR
  - ➢ "**dirty window**" (400-600 cm^{-1})

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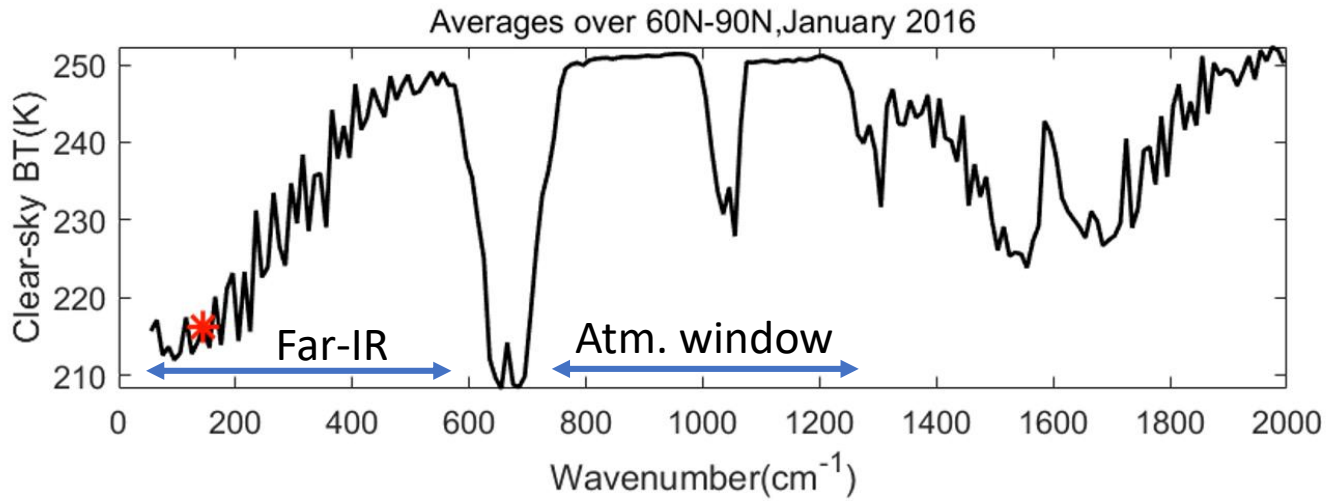
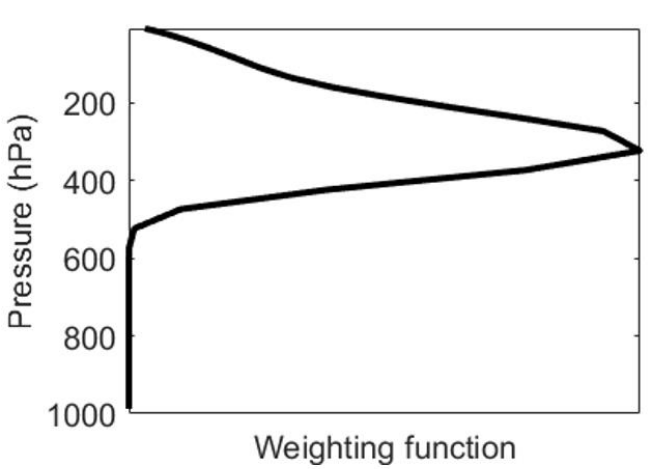
OLR and GHE through a Spectral Lens

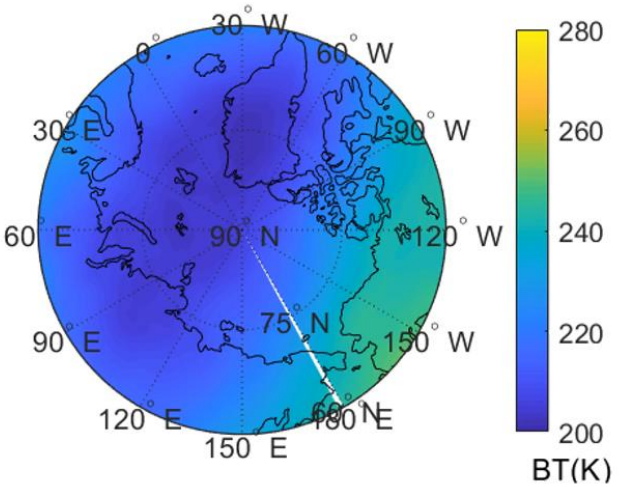
Why use spectral fluxes?

1. Identify channels that are contributing to trends in broadband OLR/GHE

2. Provides insight into atmosphere and surface changes







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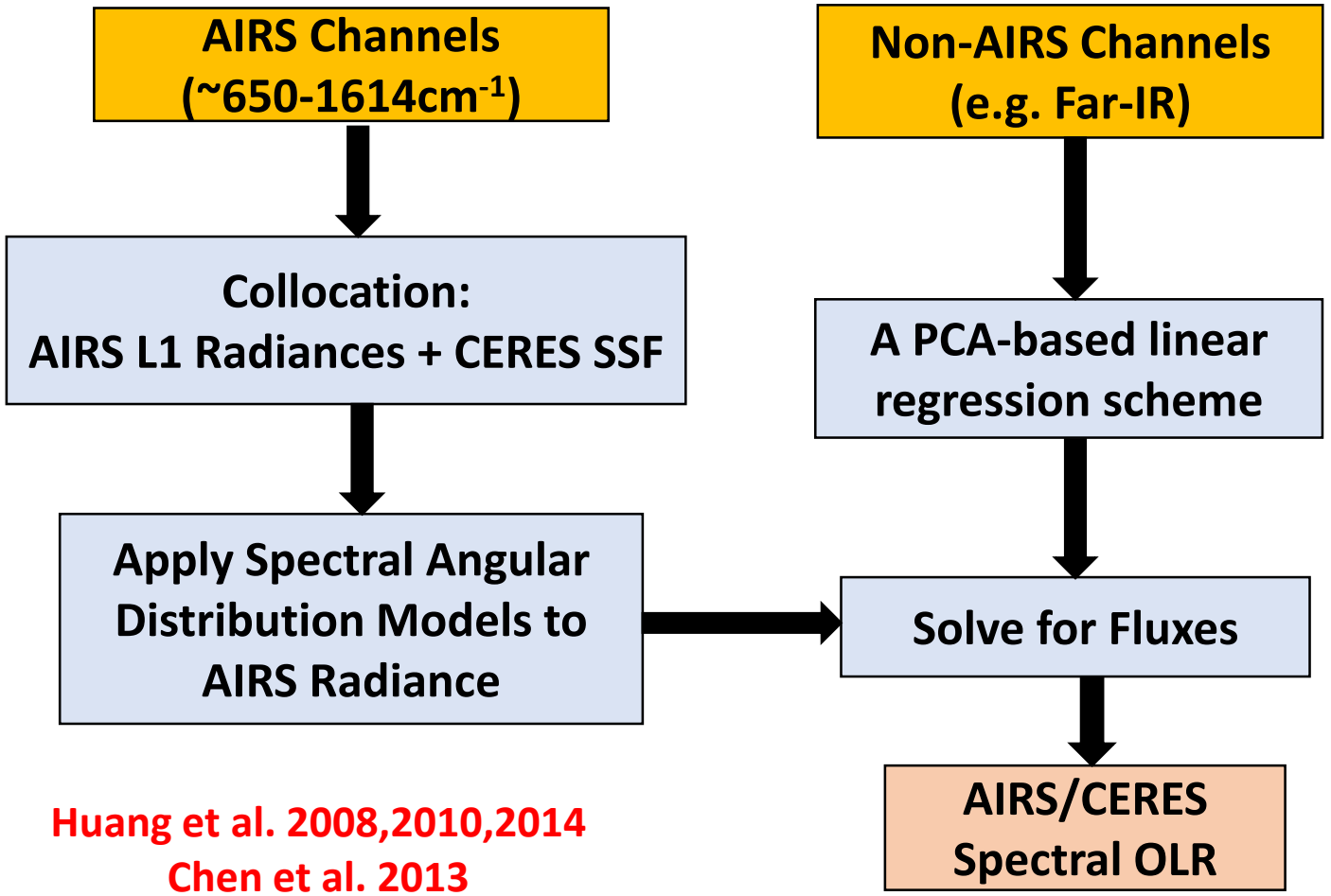
AIRS/CERES Spectral OLR Dataset

- Atmospheric IR Sounder (AIRS)
- Spectral range:
  - **10-2000 cm^{-1}** (10 cm^{-1} res.)
- Estimates of far-IR spectral flux [$W/m^2/10cm^{-1}$]
- Coverage:
  - Global **all-sky** and **clear-sky**
  - 2°x2.5° (lat,lon) grids

Spectral Flux Algorithm



Huang et al. 2008,2010,2014
Chen et al. 2013

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Methodology Outline

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1. **What Arctic environmental changes have occurred from 2003-2016?**
   - ❖ Linear trends of zonal/monthly mean AIRS L3 T_s, Q_{H2O}, T_{atm} retrievals
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2. **Arctic Spectral OLR/GHE trends ("Observed")**
   - ❖ AIRS/CERES Spectral OLR
   - ❖ Spectral GHE (AIR L3 derived $F_s^{\uparrow}$)

$$\text{GHE}(\nu) = \frac{F_s^{\uparrow}(\nu) - OLR(\nu)}{F_s^{\uparrow}(\nu)}$$

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4. **Sensitivity Analyses (Connect geophysical variable trends to OLR/GHE trends)**
   - Vary one L3 variable at a time
   - Compute OLR and GHE trends due to a particular variable

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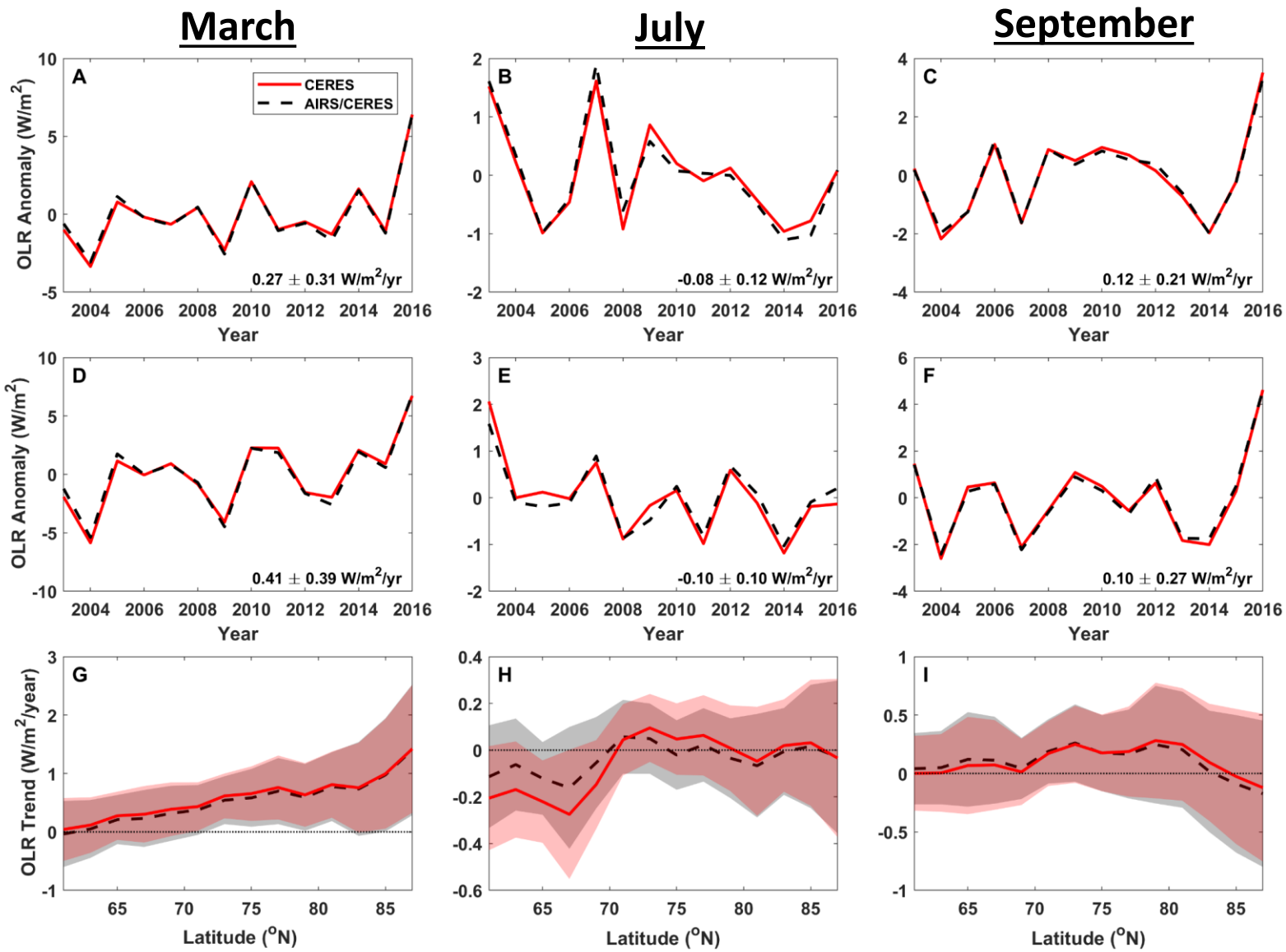
Broadband OLR Comparisons: Spectral Product vs. CERES SSF Edition4



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AIRS L3 Retrieval Trends Analysis

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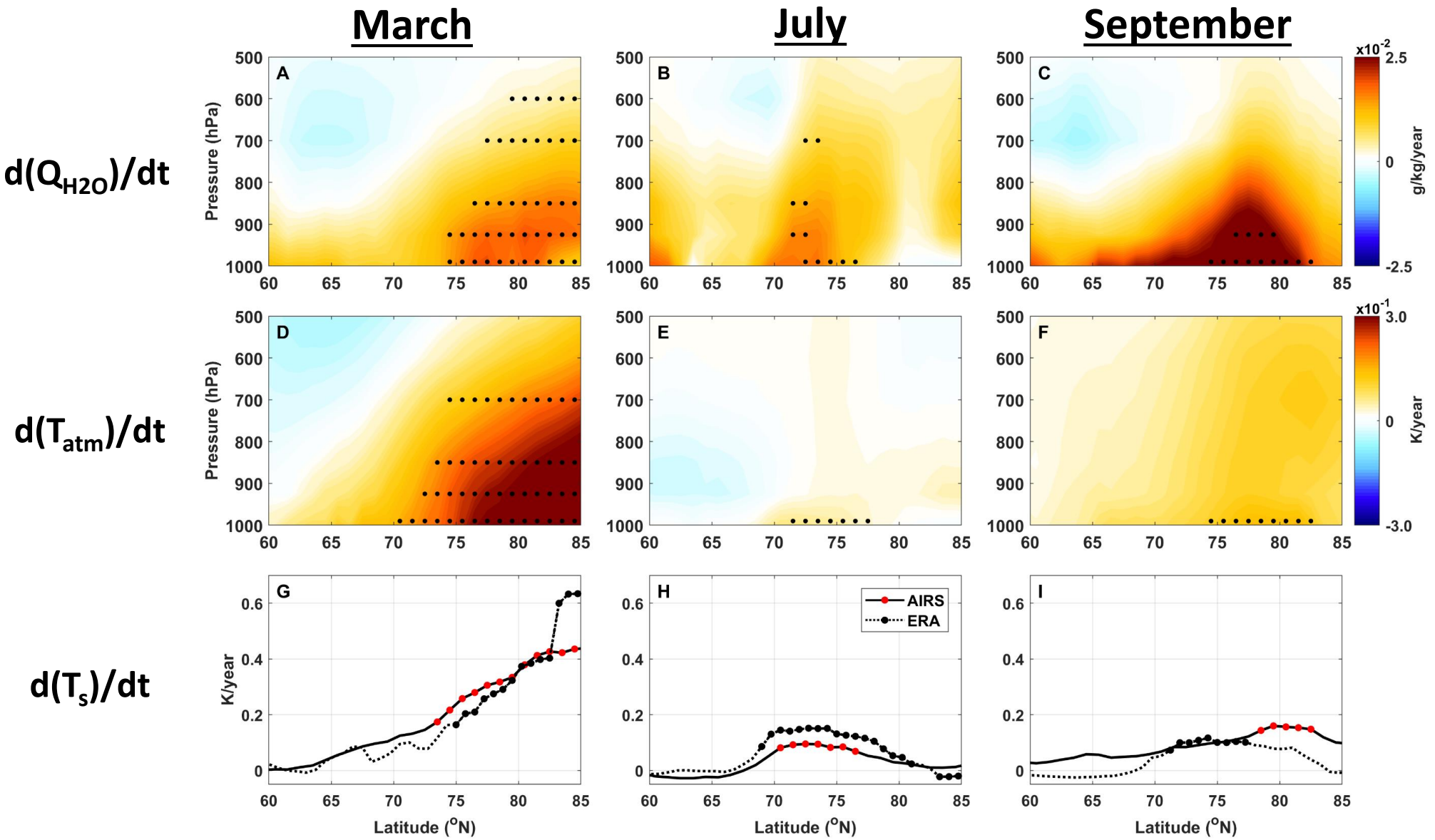
AIRS L3 Trend Results: A Warmer & Wetter Arctic

Key Points

- Positive trends in all months
- Springtime warming consistent with previous studies
- March shows widespread and significant changes



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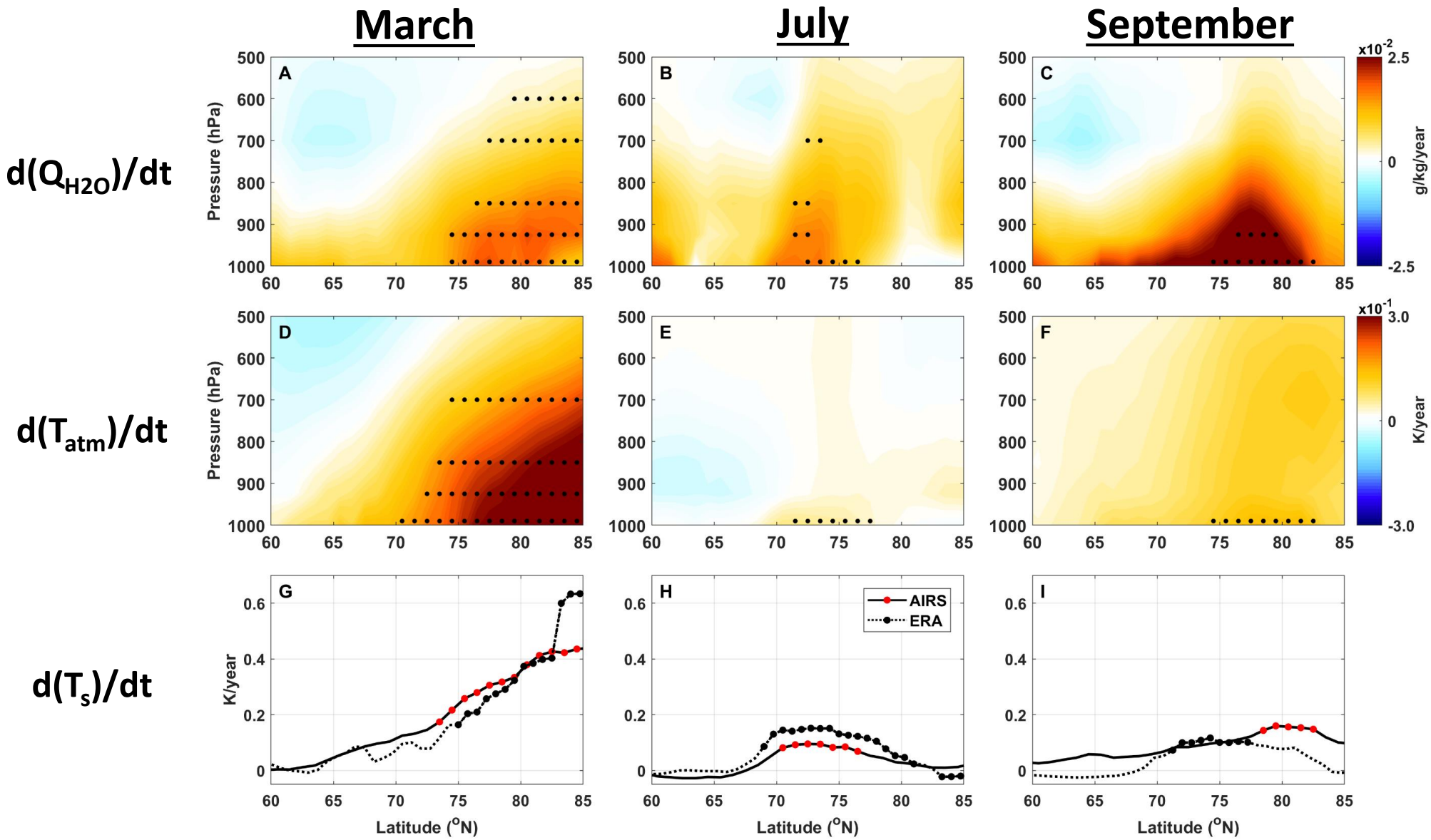

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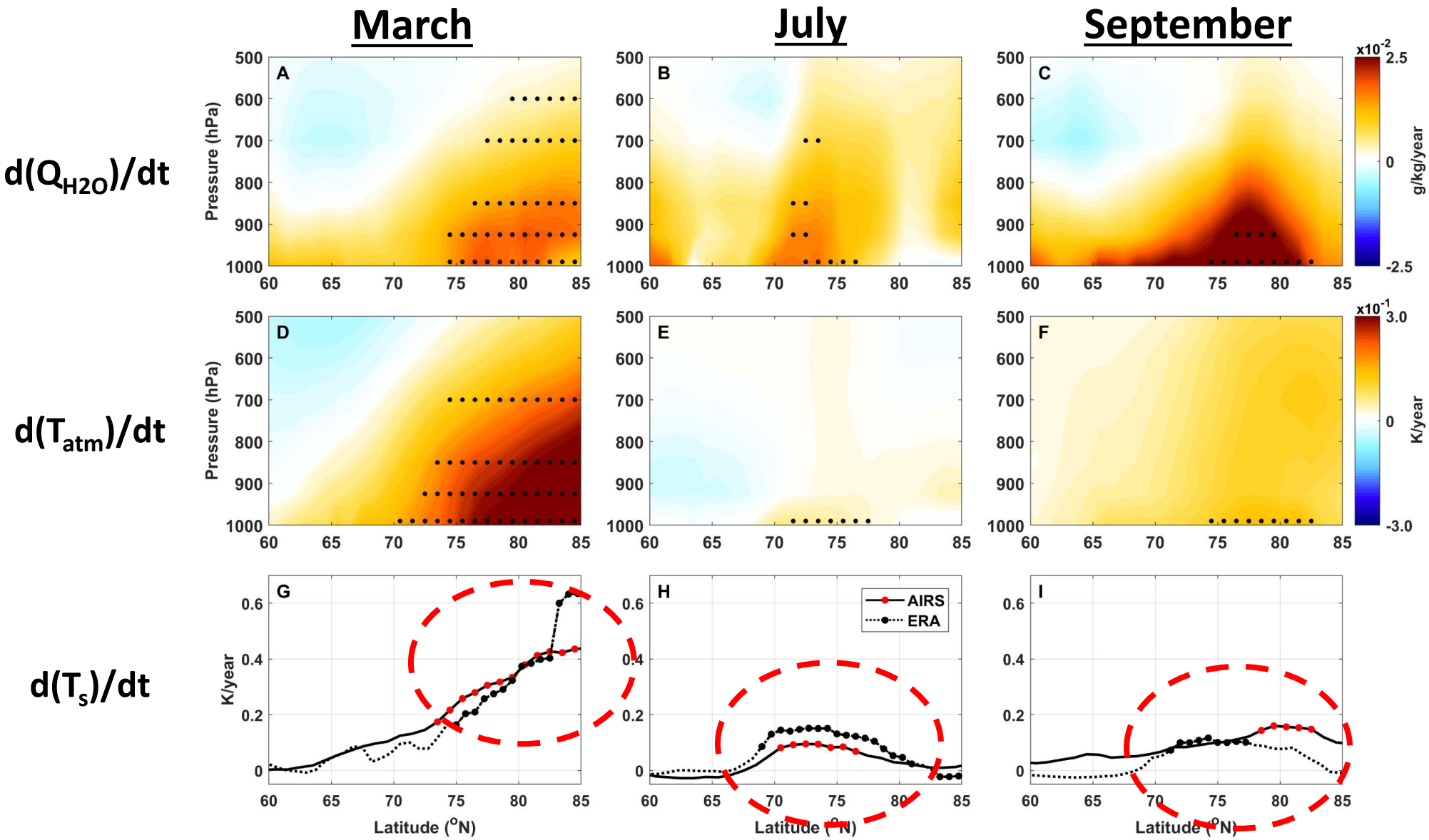

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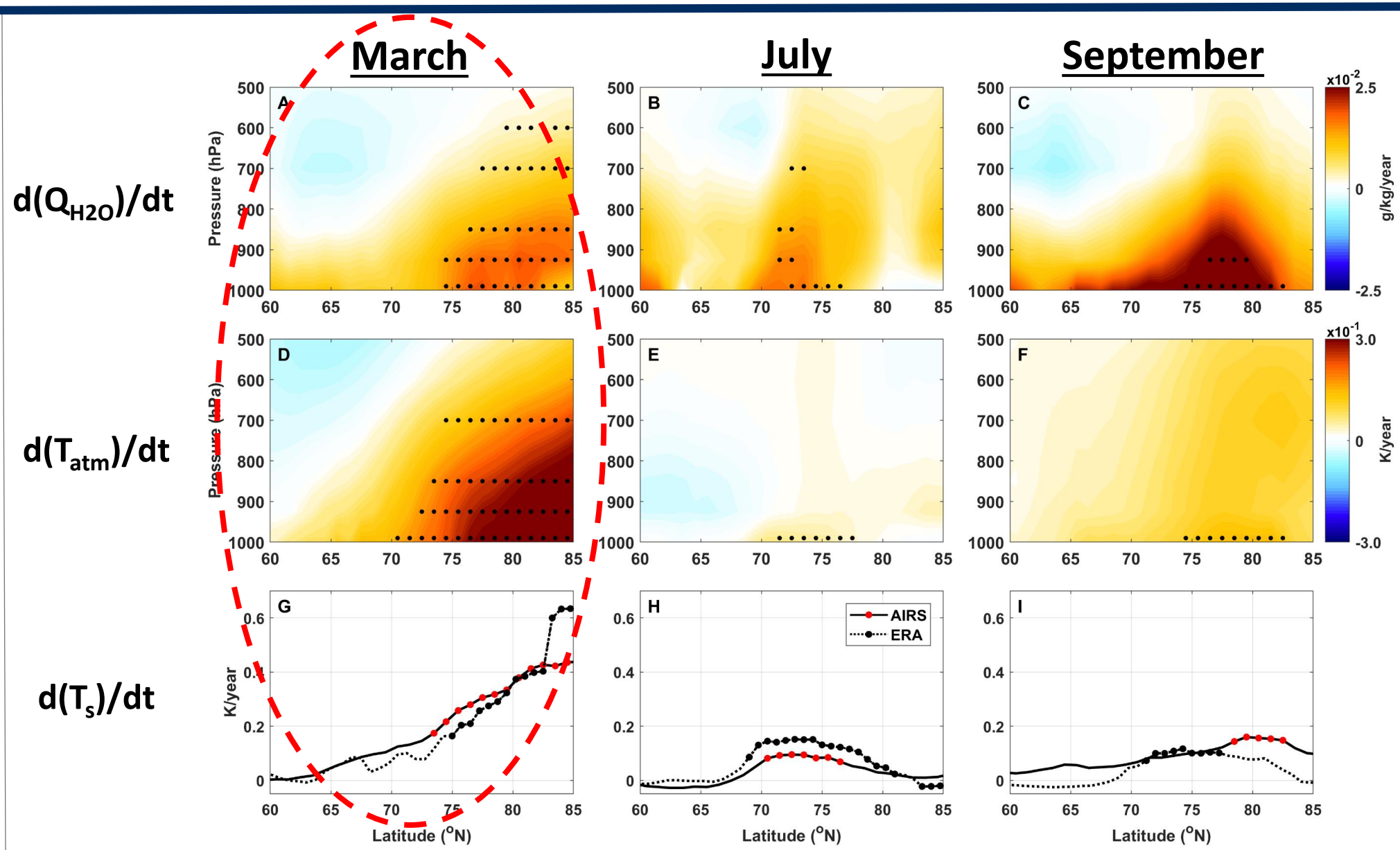

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1. Emphasis on March

- ❖ Clear-Sky Spectral OLR and GHE Trends
- ❖ Sensitivity Simulations

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2. Inter-seasonal Comparison

- The Nuances of Q_{H2O} Radiative Effects
- Utility of spectral fluxes

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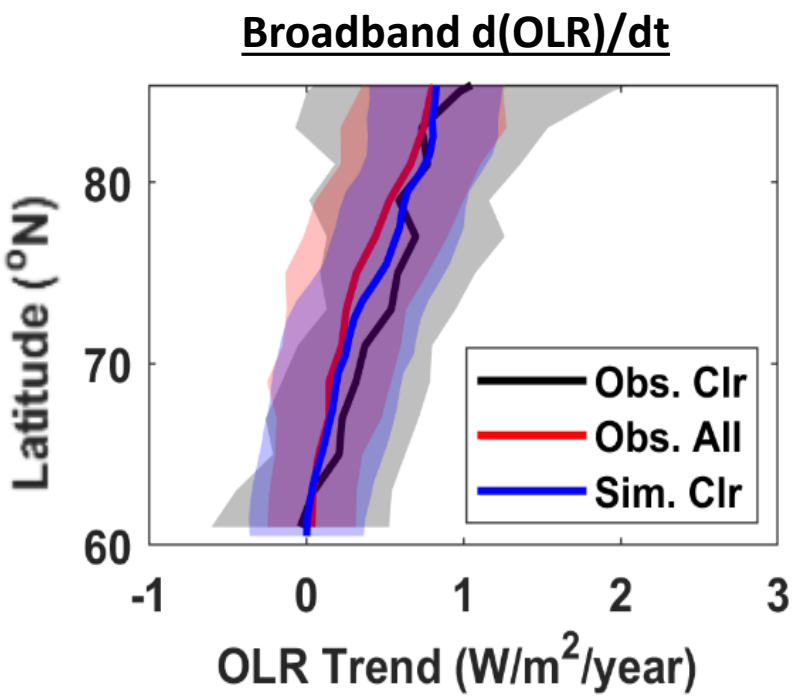
March OLR Trends: Increases in Window Regions



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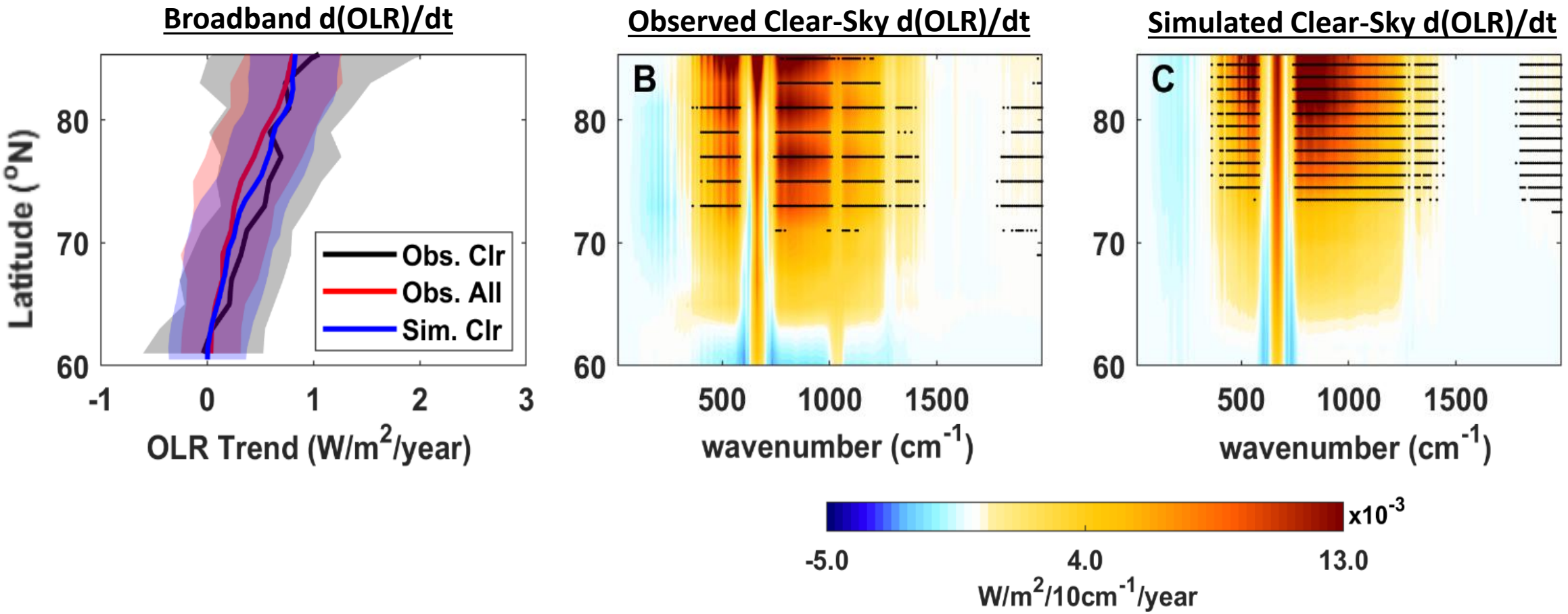

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March Greenhouse Efficiency Trends

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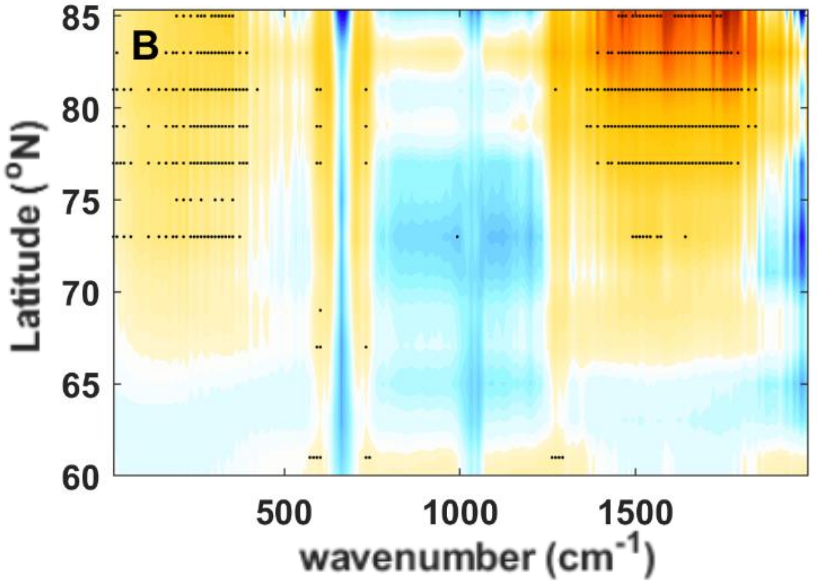
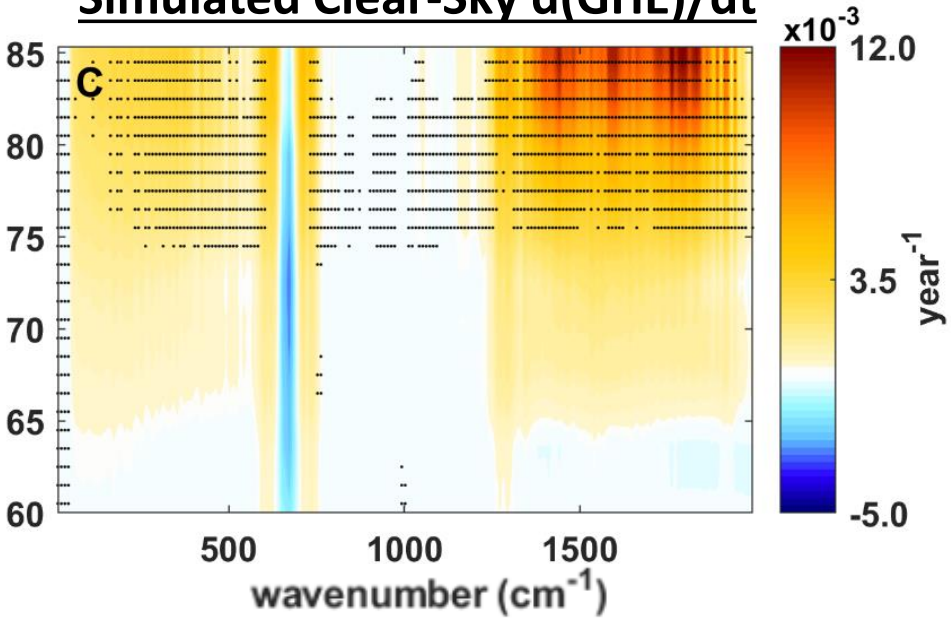
March GHE Trends: OLR & $F_s^{\uparrow}$ Compete

Observed Clear-Sky d(GHE)/dt



Simulated Clear-Sky d(GHE)/dt



Key Points:

1. OLR and GHE trend patterns are distinct
2. Positive trends across H_2O bands
3. Changes in OLR and $F_s^{\uparrow}$ compete

d(GHE)/dt is positive if: $\frac{d(OLR)/dt}{OLR} < \frac{d(F_s^{\uparrow})/dt}{F_s^{\uparrow}}$

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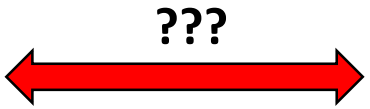
March Sensitivity Analysis

OLR/GHE Trends 

T_s, Q_{H2O}, T_{atm}

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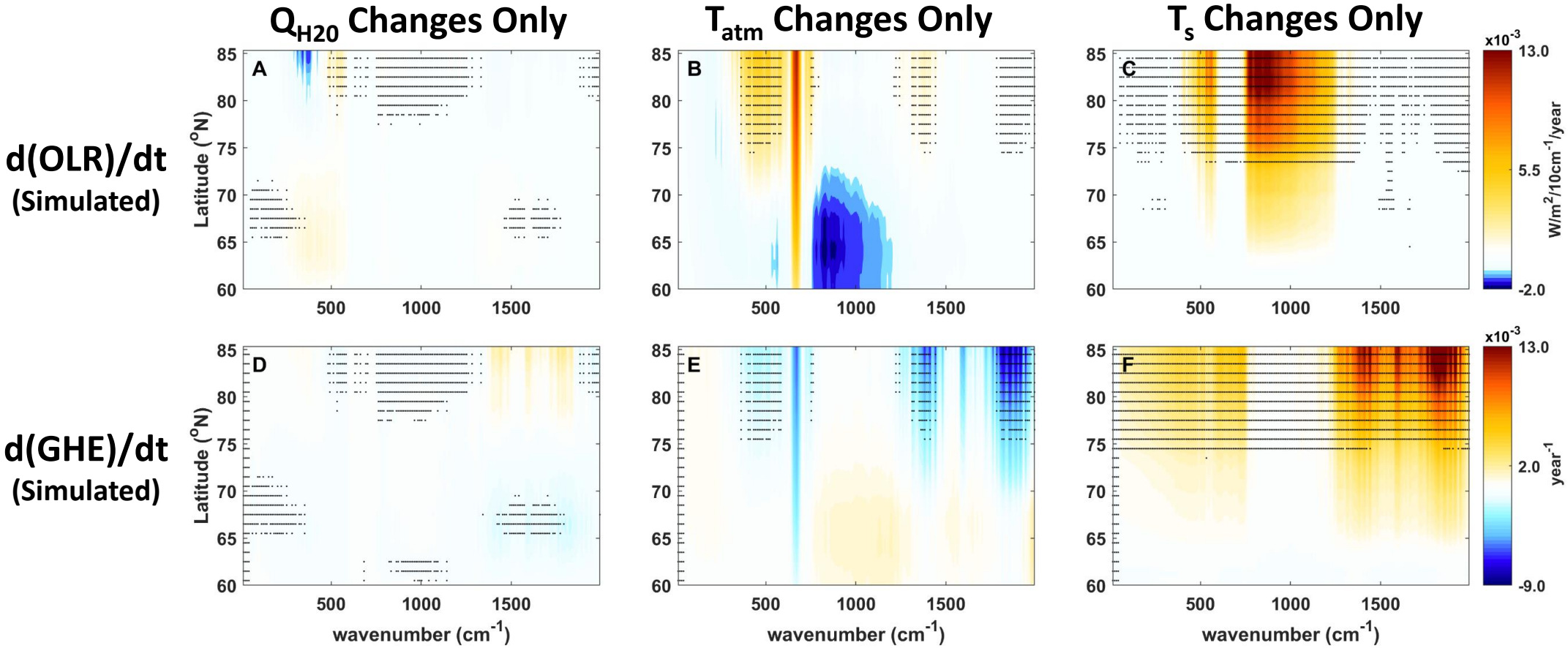
March Sensitivity Analysis Overview: T_s Dominates



Key Points:

1. T_s dominates OLR and GHE trends (March, July, Sep)
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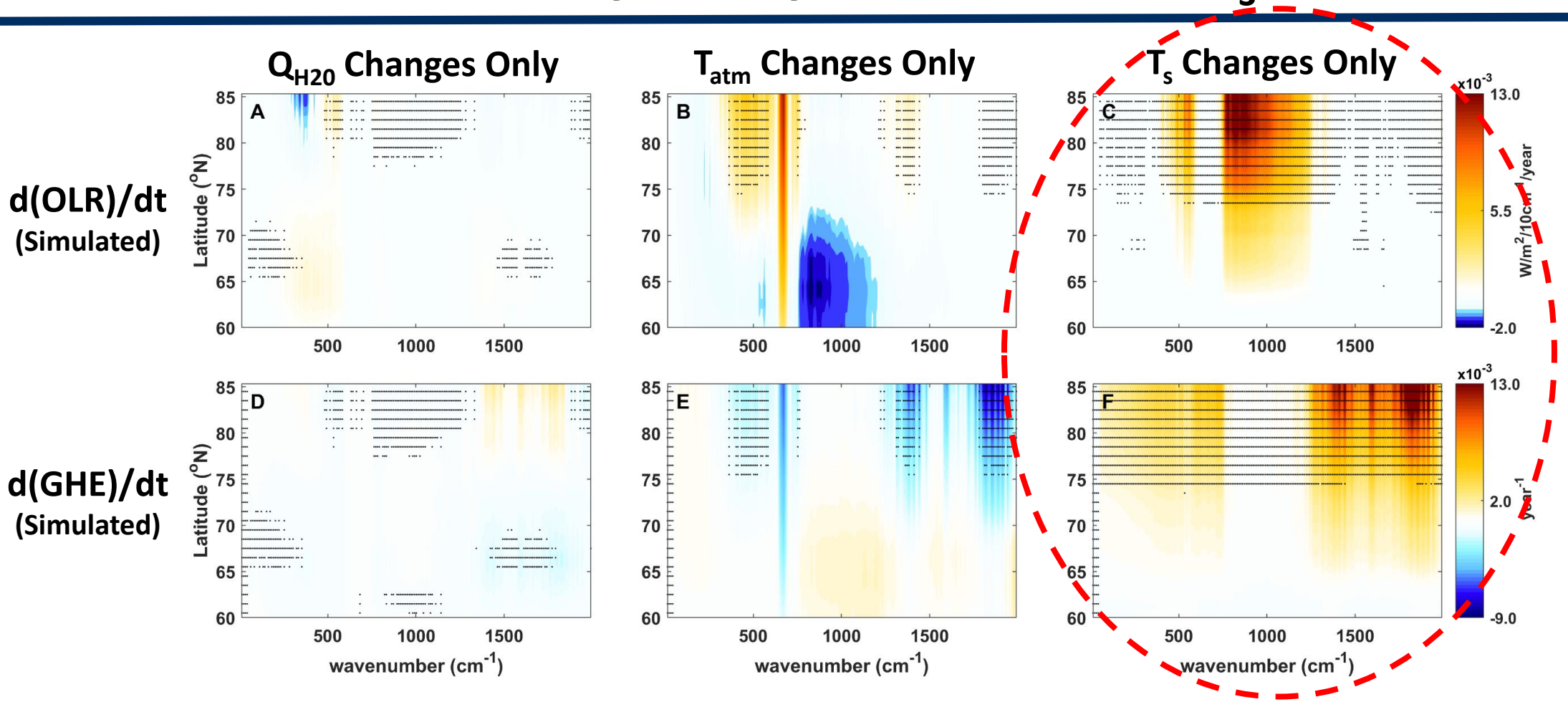

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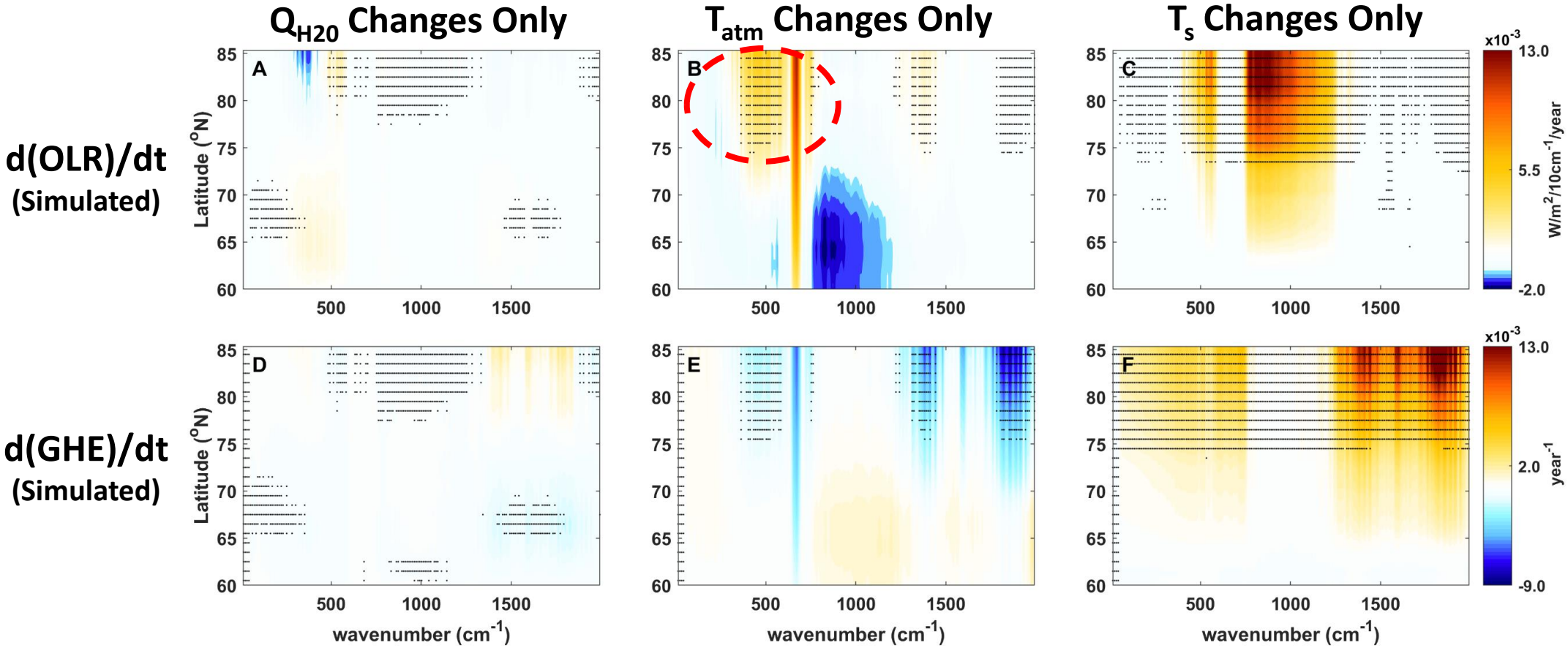

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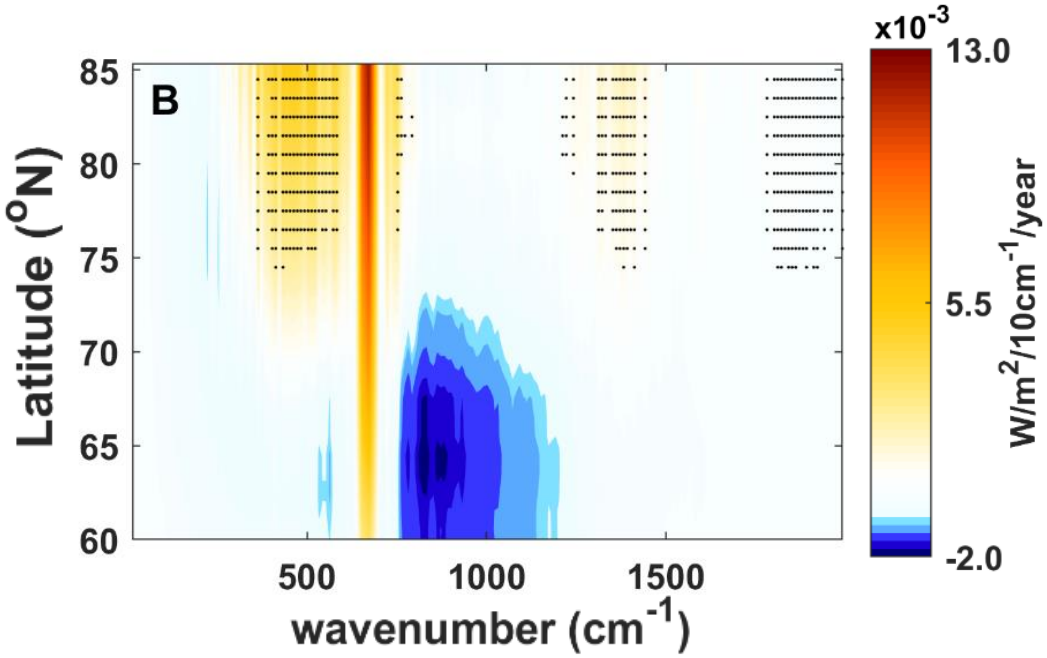
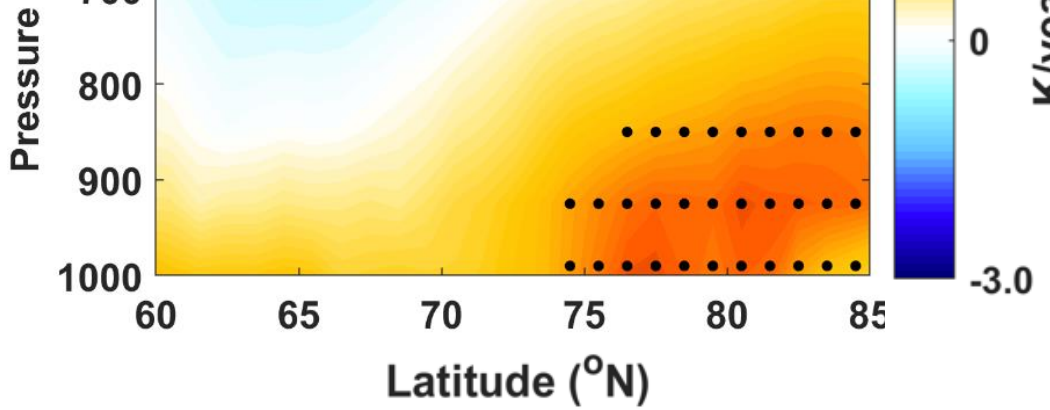
March T_{atm} Impacts: Far-IR Emission and a Warming Troposphere

Simulated OLR Trends (T_{atm} Only)





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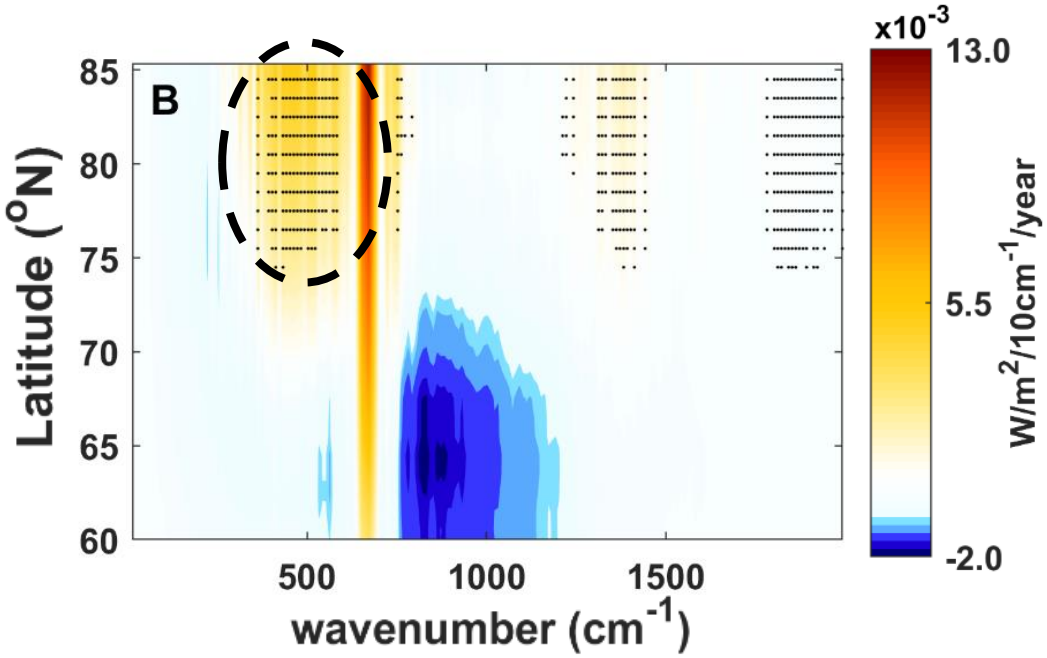

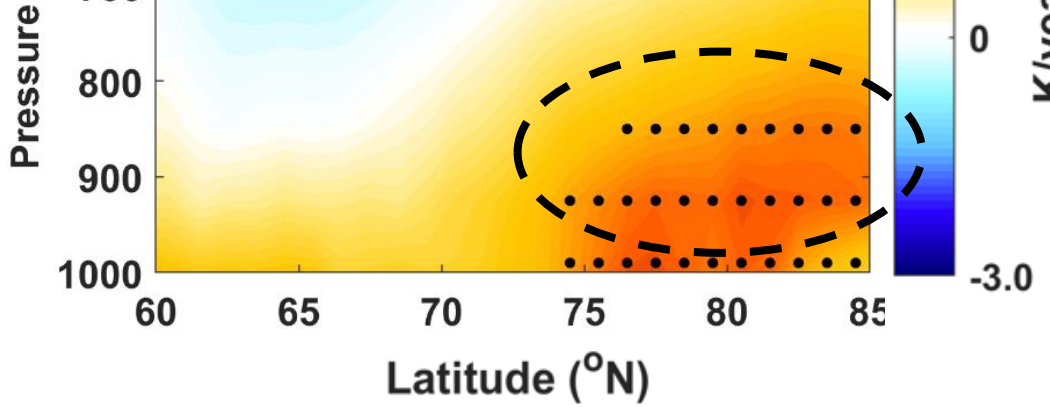

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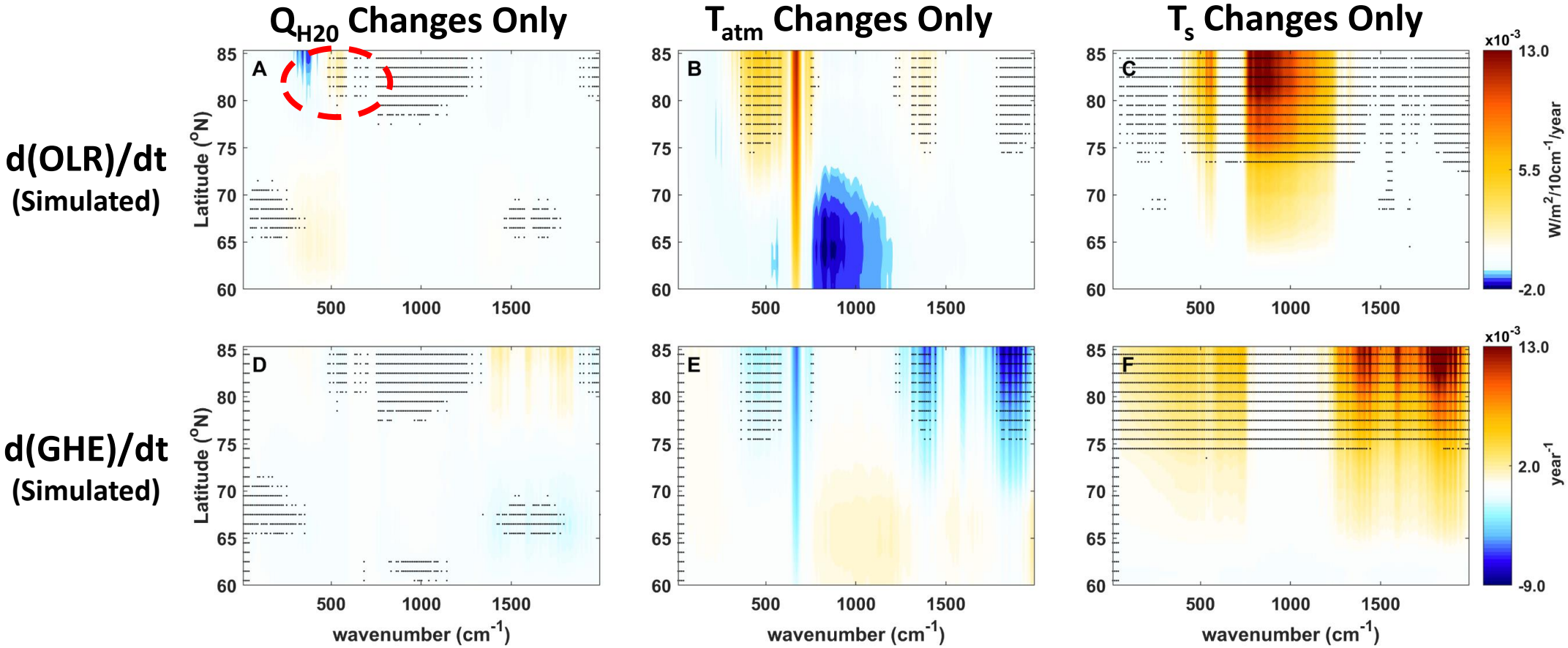

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Seasonal Differences of the Humidity-OLR Trend Relationship

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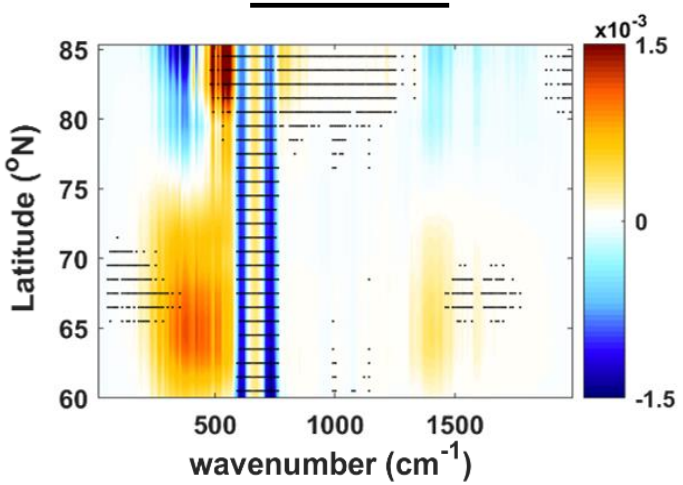
OLR changes depend on the seasonality & pressure level of Q changes

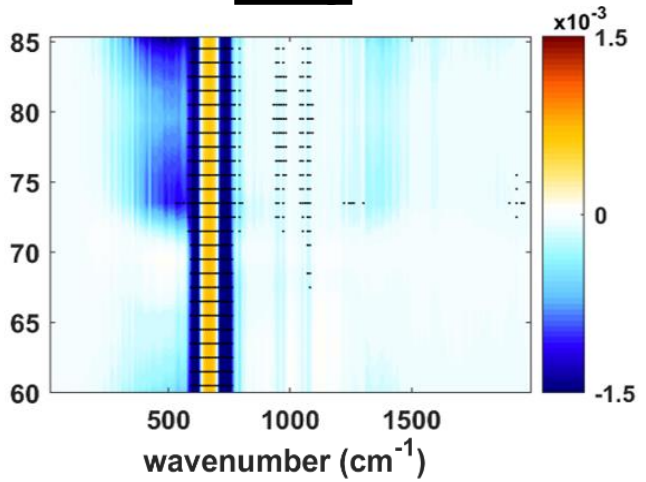
d(OLR)/dt

(Q_{H2O} varies only)

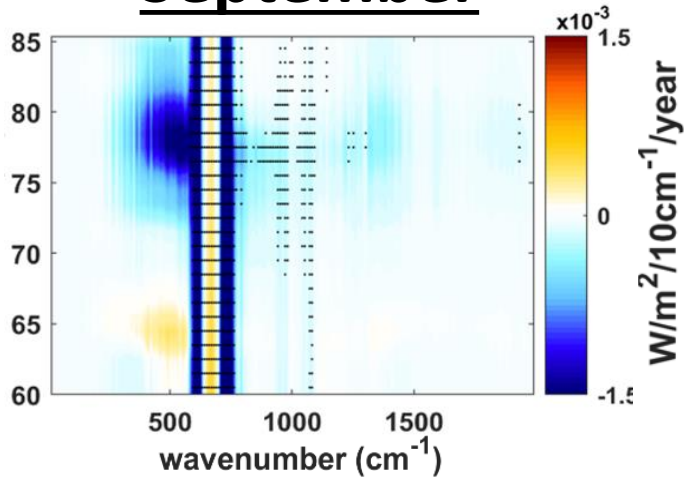
March



July



September



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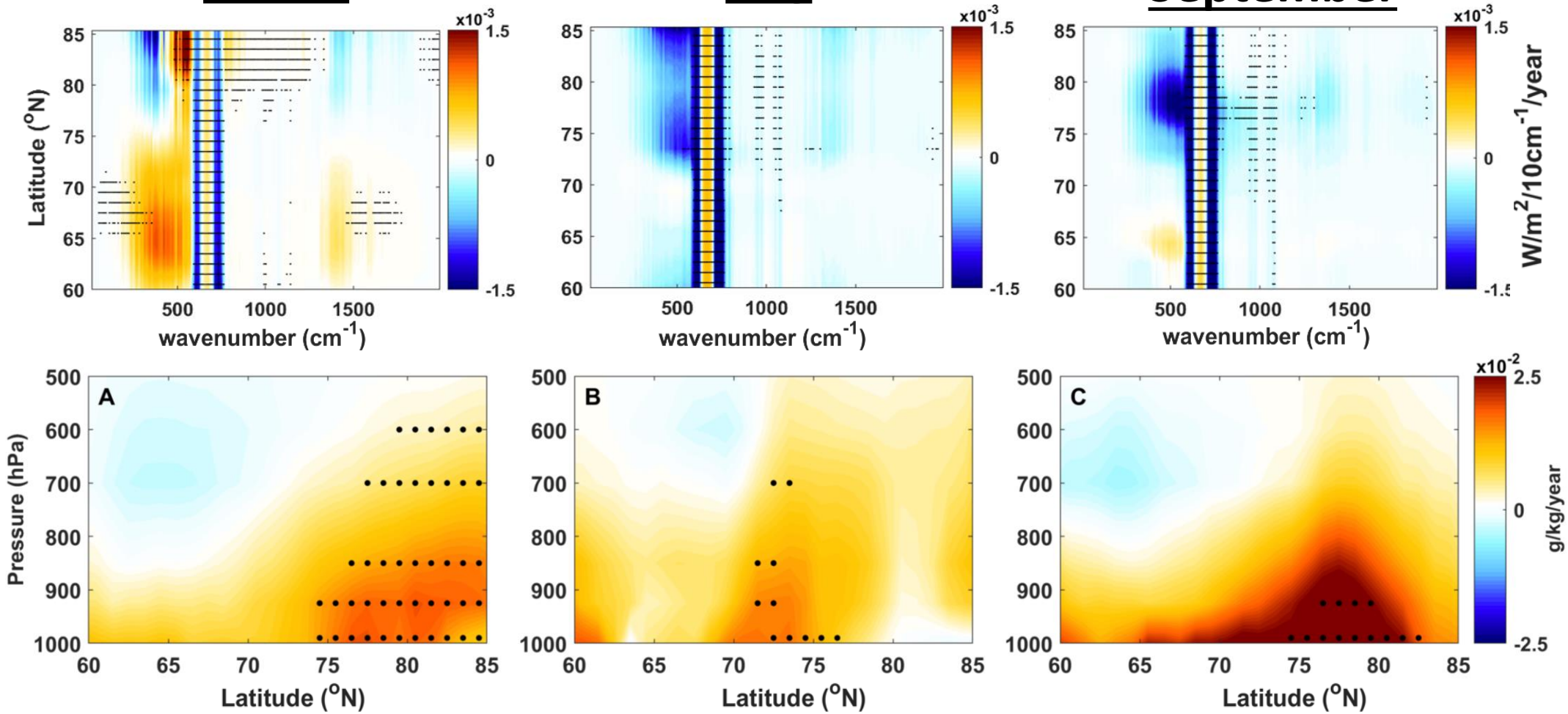

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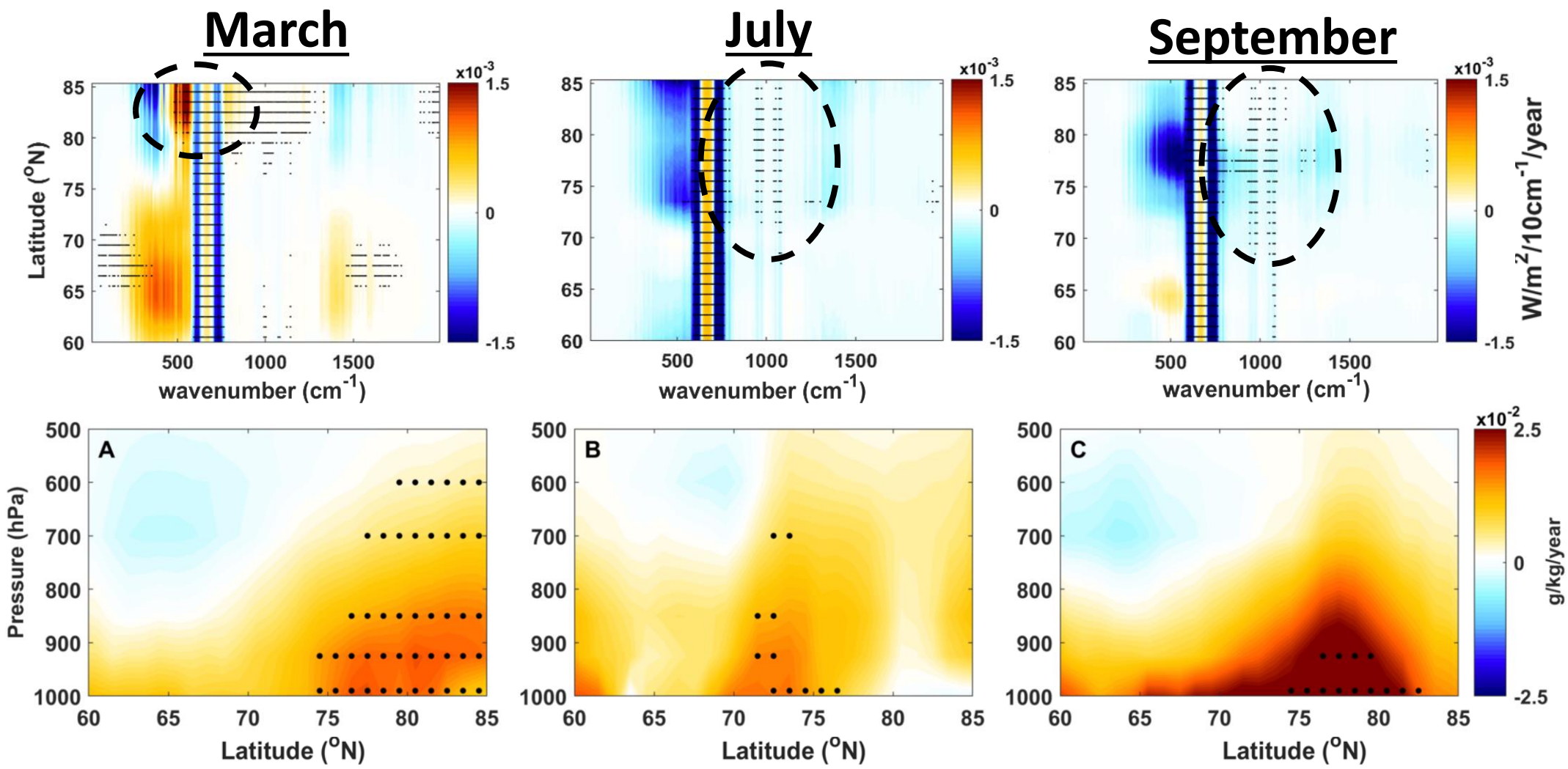

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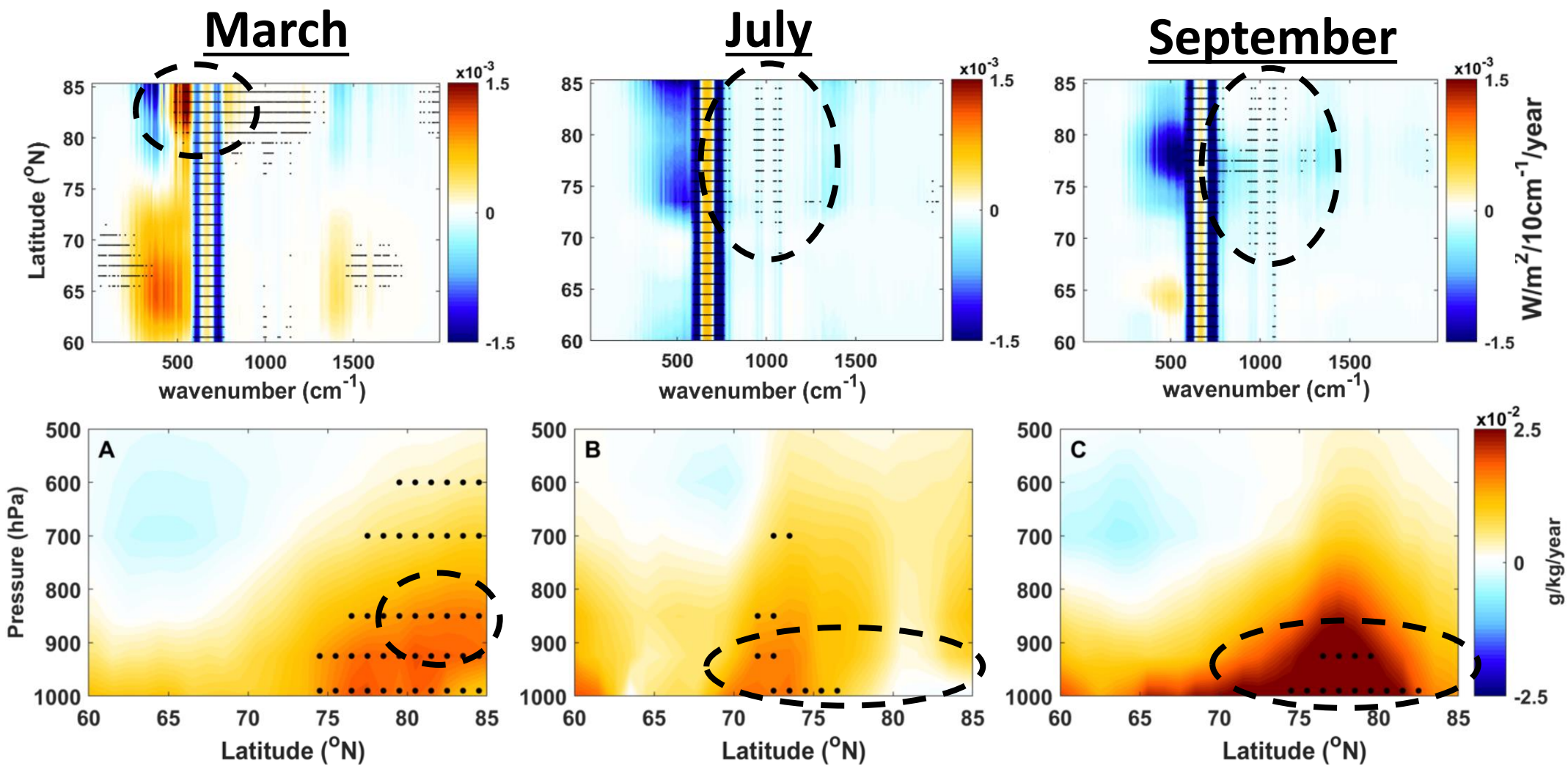

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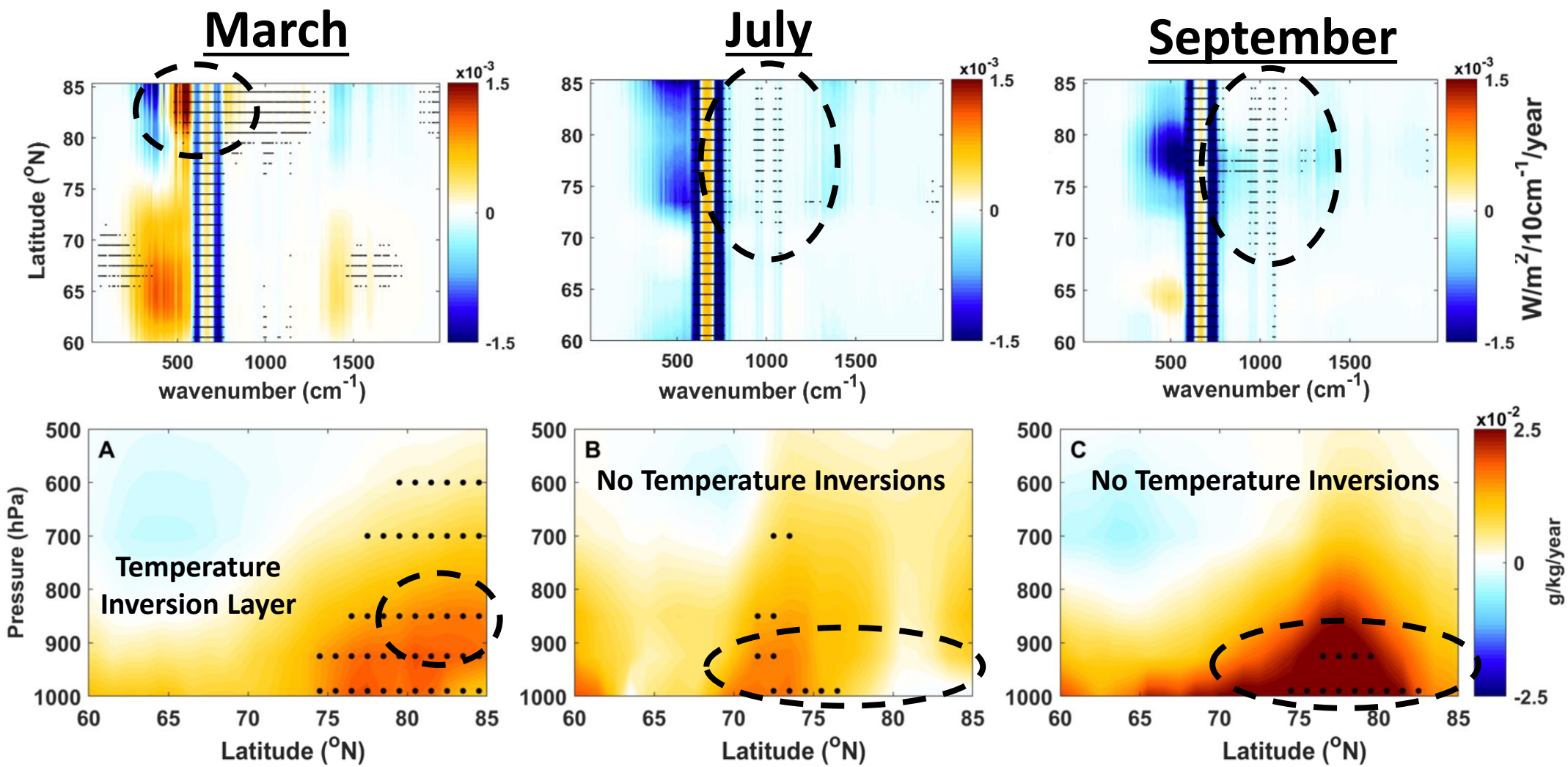

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Conclusions

1. **Arctic is shifting to a warmer, wetter state**
   - Increasing surface temperatures, humidity, and tropospheric temperatures
2. **OLR and GHE trends have distinct features**
   - Across LW frequencies, latitudinal zones, seasons
3. **Surface Temperature dominates OLR and GHE trends**
   - Important in the context of Arctic amplification
   - Surface warming causes both OLR and GHE to increase!
4. **Spectral dimension offers insight for the Arctic**
   - Supplement broadband measurements
   - Attribute radiative energy budget changes
   - Far-IR can peer deeper into Arctic atmosphere

Future Opportunities : (1) Apply methods to a spectral feedback study
(2) Climate change detection and attribution

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Supplementary Figures

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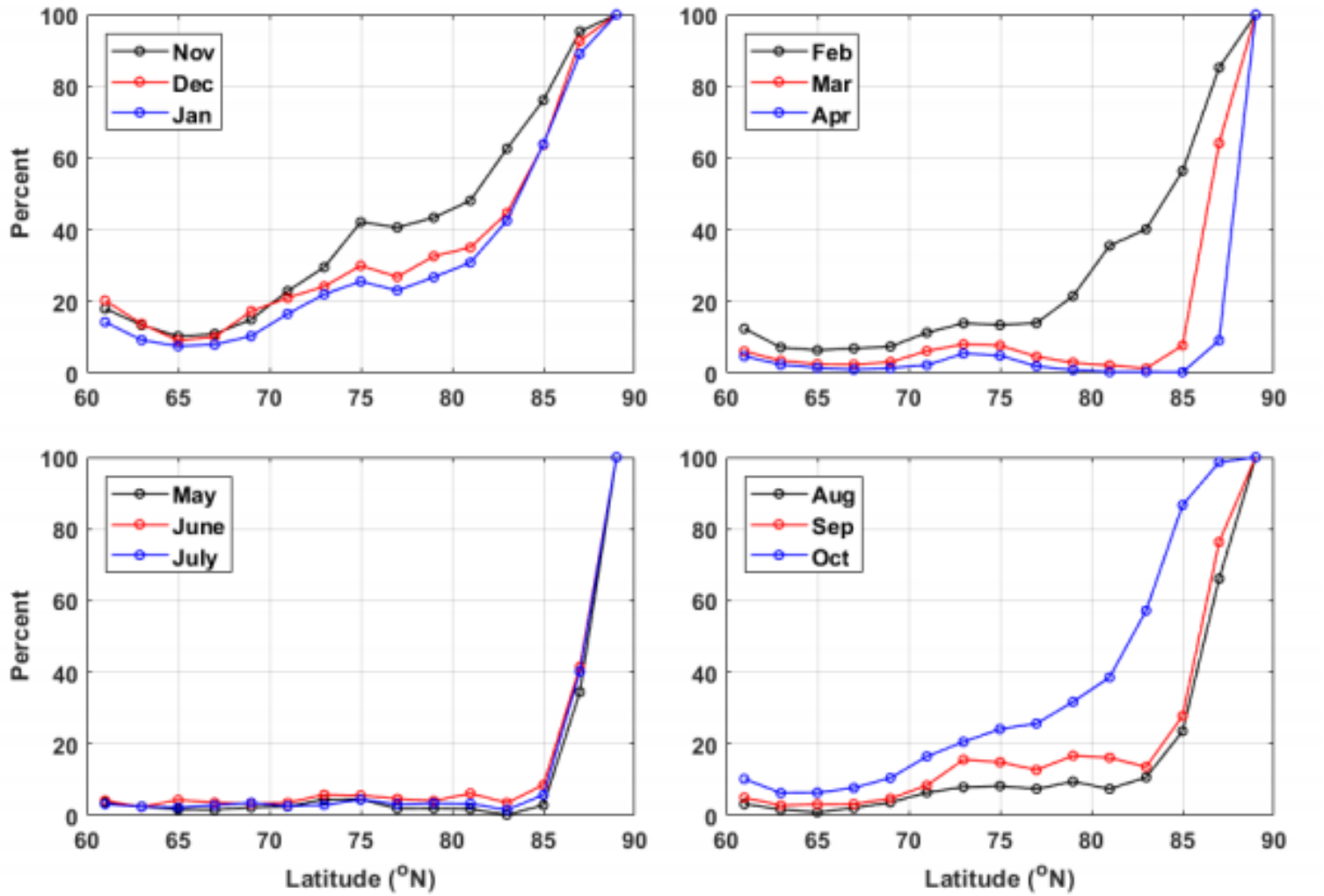
% of Grid Boxes with No Clr-sky CERES SSF



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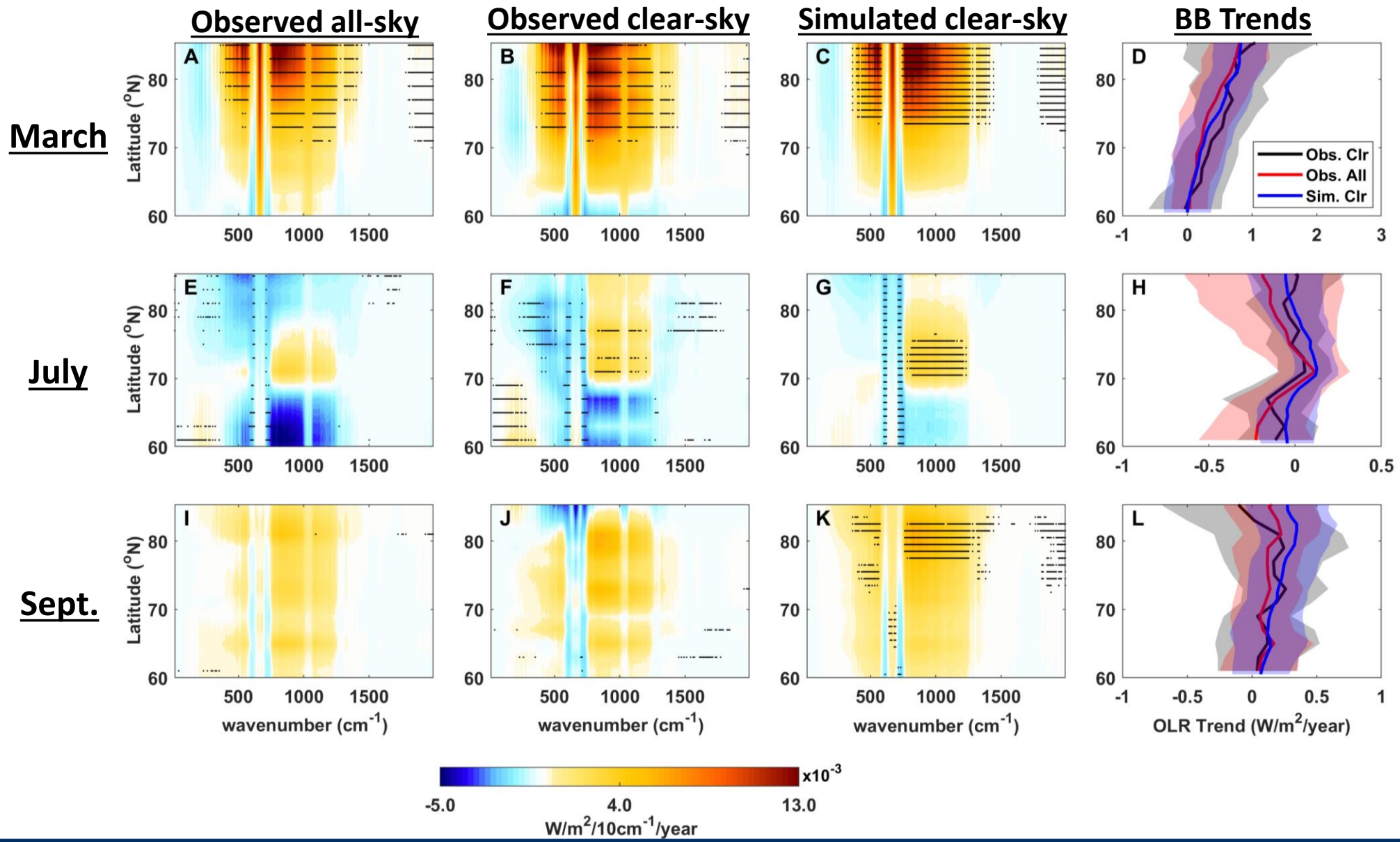
Spectral OLR Trends



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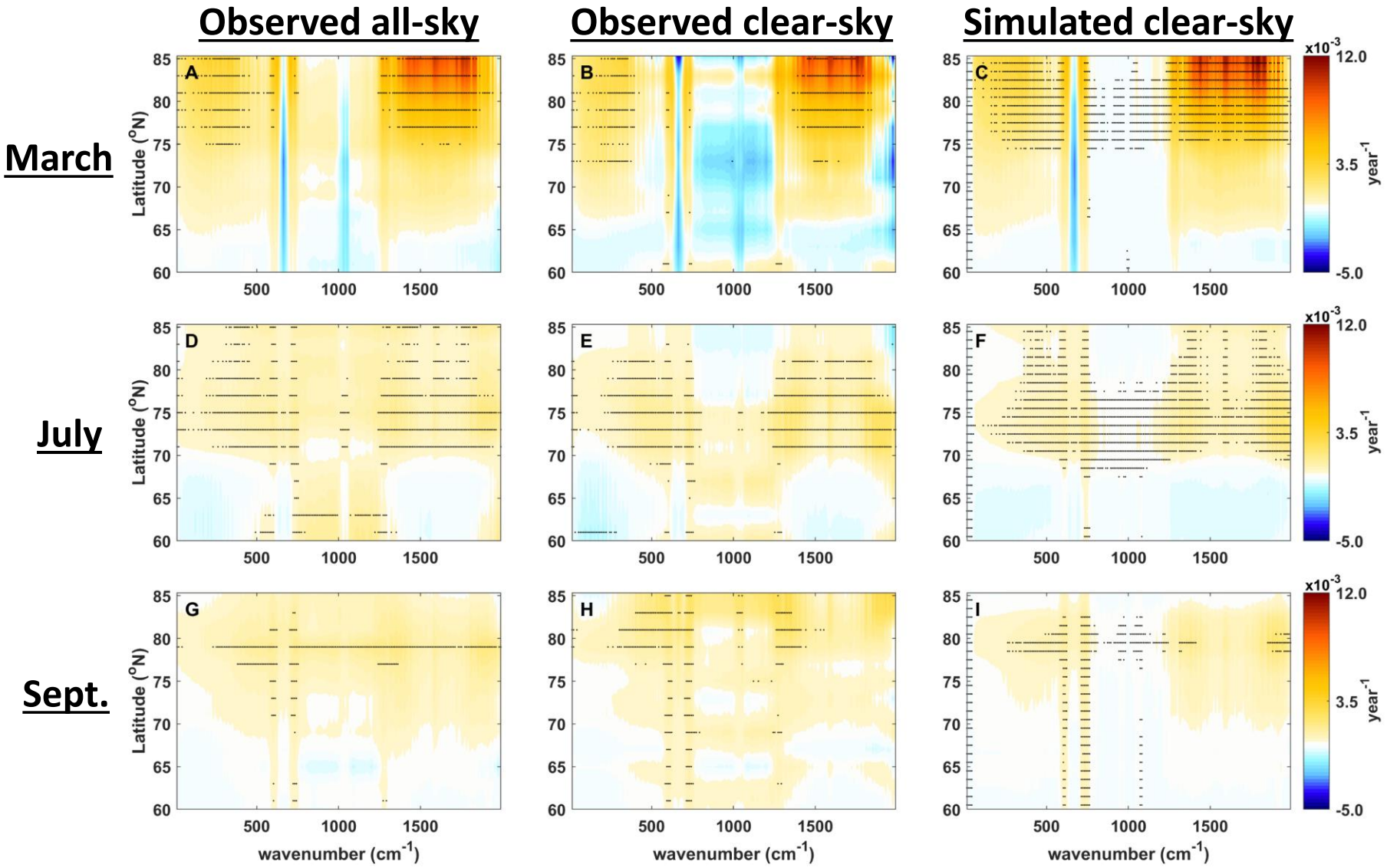
Spectral GHE Trends



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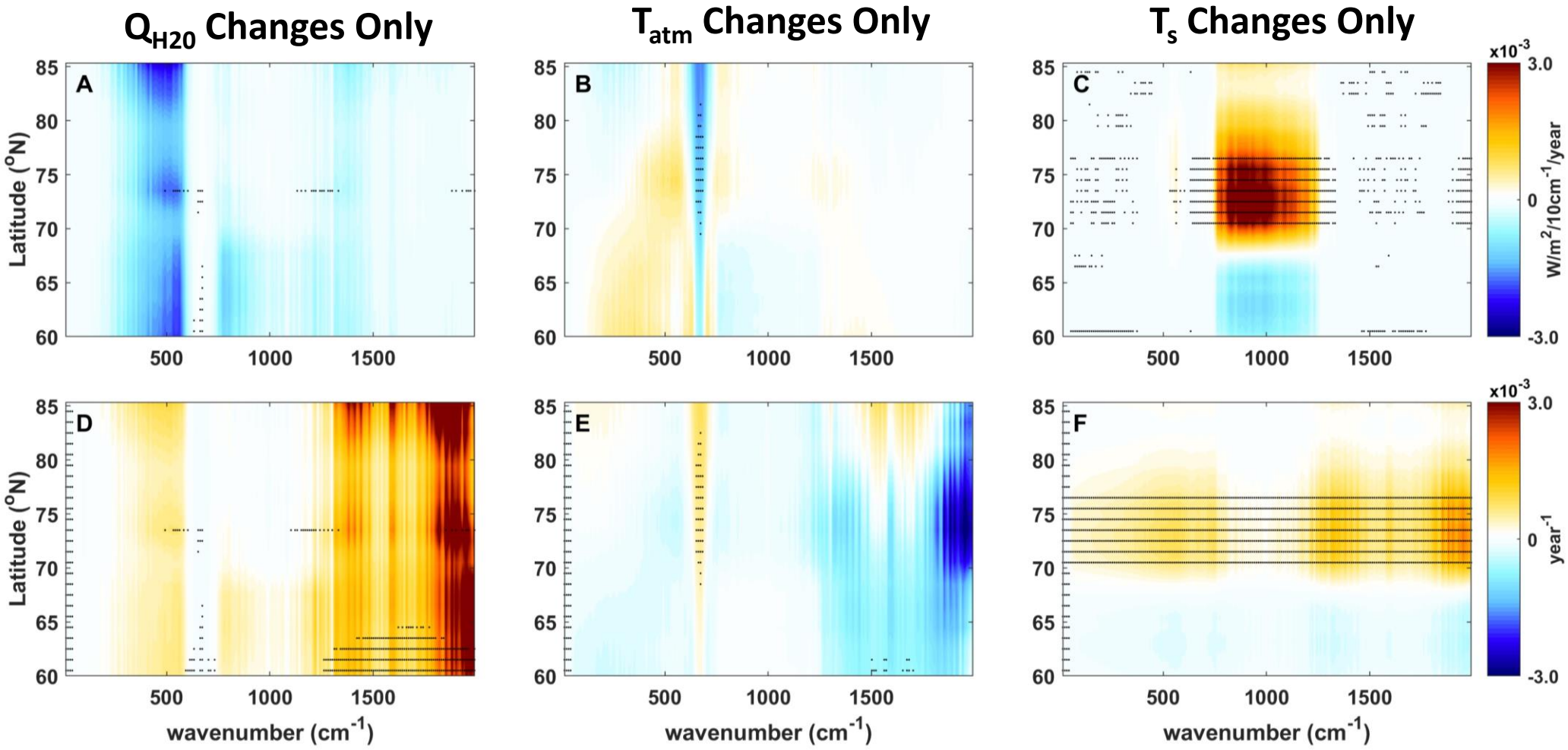
July Sensitivity Analysis



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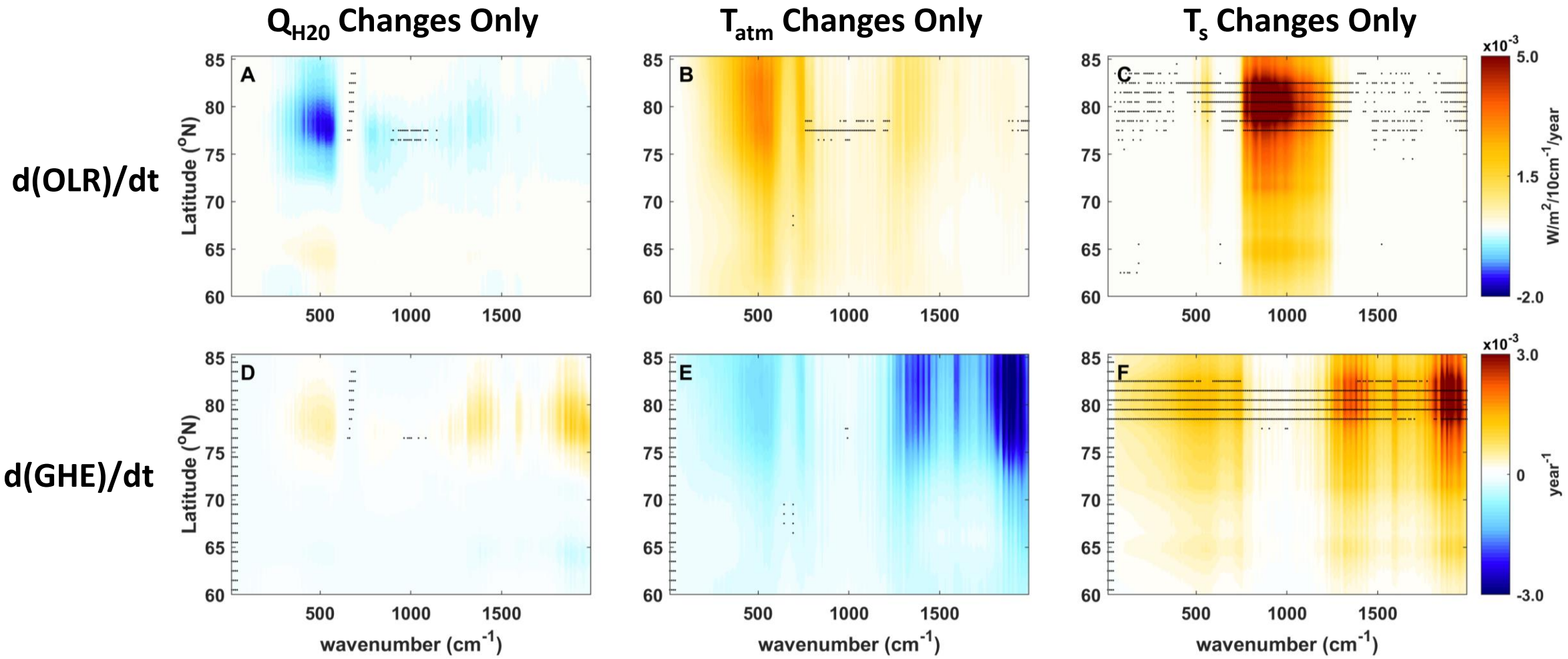
September Sensitivity Analysis



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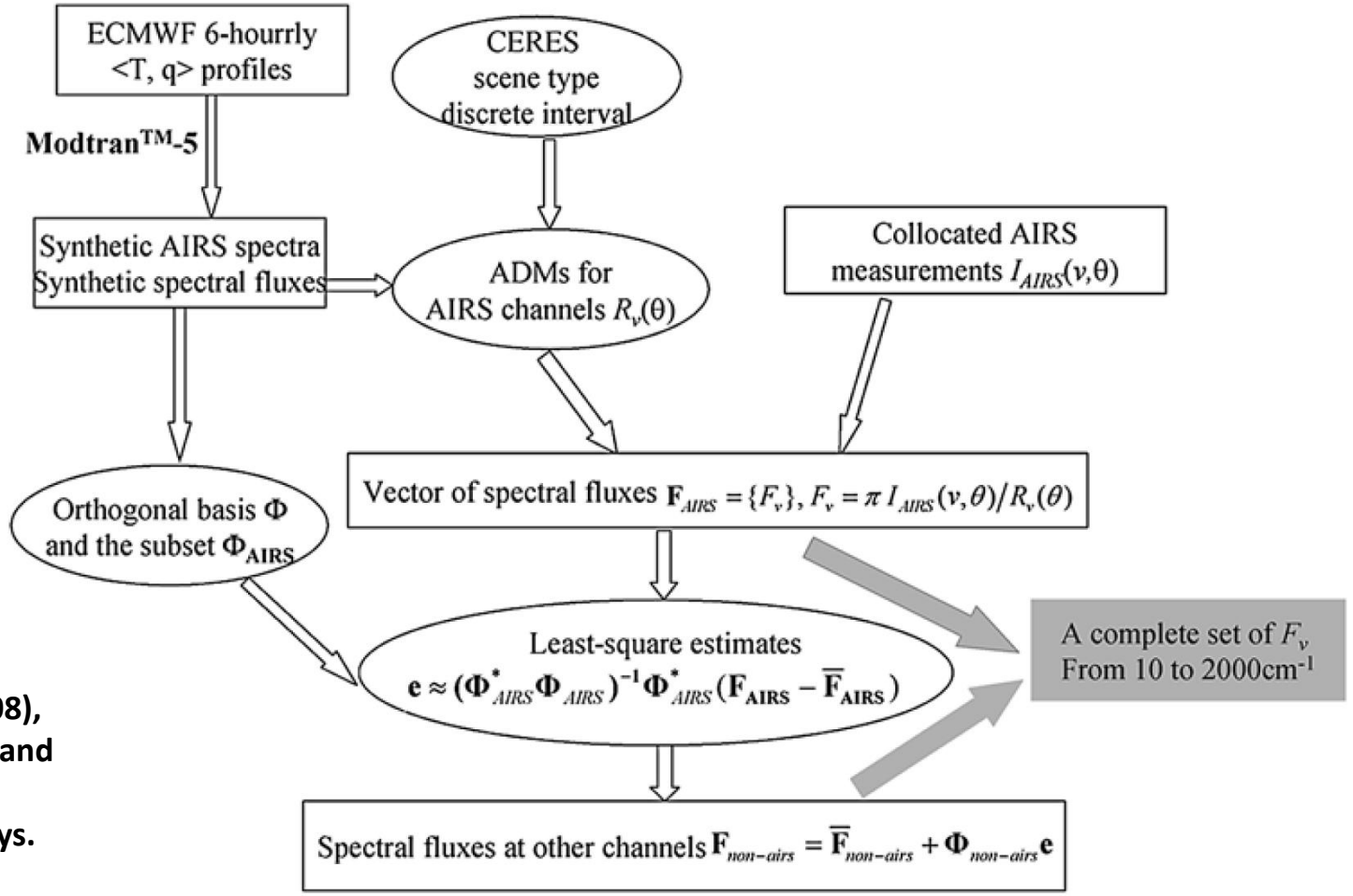
AIRS-CERES Spectral OLR Algorithm Details

$$F_v = \bar{F}_v + \sum_{j=1}^{N} e_j \phi_v^j$$

$$\mathbf{F} - \bar{\mathbf{F}} \approx \left[\phi^1, \phi^2, \ldots, \phi^M\right] \begin{bmatrix} e_1 \\ e_2 \\ \cdots \\ e_M \end{bmatrix} = \Phi e$$

$$\mathbf{F}_{AIRS} - \bar{\mathbf{F}}_{AIRS} \approx \Phi_{AIRS}\mathbf{e}$$

99.99% of variance can be explained by the first 20 or even less PCs



Huang, X., W. Yang, N. G. Loeb, and V. Ramaswamy (2008), Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation: Clear sky over the tropical oceans, J. Geophys. Res., 113, D09110, doi:10.1029/2007JD009219

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PCRTM Basics

- Ensemble of atmospheric profiles used to generate radiance spectra
- Matrix formed with N spectra and M channel radiances

- SVD performed to retrieved PCs (orthogonal basis vectors)
  - Compression of spectral information
  - ~10^2 PCs needed
  - PCs stored in forward model

- Linear combination of PC scores (Y_i) and PCs (U_i) generate channel radiances

$$\vec{R}^{ch} = \sum_{i=1}^{N_{PC}} Y_i \vec{U}_i + \vec{\varepsilon} = \sum_{i=1}^{N_{PC}} \left(\sum_{j=1}^{N_{mono}} a_j R_j^{mono} \right) \vec{U}_i + \vec{\varepsilon}$$

- Correlation function used to select frequencies for R^{mono} computation

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Synthetic Spectral Flux Calculations

- AIRS Level 3 Retrievals
  - Day/night monthly mean profiles
  - Gridded at 1deg x 1deg
  - T_{atm} is reported at 24 levels (1000hPa – 1hPa)
  - Q is reported at 12 levels (1000-100hPa)

- PCRTM produces spectra in compressed PC score format
- Spectrum generated at $1cm^{-1}$ intervals using PCs and scores
- Summed to $10cm^{-1}$
- Average day/night to get monthly mean

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